AN EXPERIMENTAL INVESTIGATION OF THE DUAL CHAMBER ROCKET

James Francis McFillin

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN EXPERIMENTAL INVESTIGATION
OF THE DUAL CHAMBER ROCKET

by

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An Experimental Investigation of the Dual Chamber Rocket

by

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Lieutenant, United States Navy
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An experimental investigation was conducted to determine the feasibility and practicality of the dual rocket motor concept. Cold flow studies were performed with the aid of a ground-test simulator which incorporated a telescoping booster cavity. The effects of booster cavity length, booster cavity shockdown pressure, booster/sustainer nozzle area ratios, and aft nozzle removal on thrust and performance were explored and discussed.

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TABLE OF SYMBOLS

A = Area

d = Diameter, in.

F = Thrust, lbf.

L = Length, in.

$\dot{m}$ = Flowrate

P = Pressure, lbf./in.^{2} absolute

T = Temperature, °R

Subscripts:

b = Booster

e = Nozzle exit

j = Jet

s = Sustainer

sh = Shockdown

t = Nozzle throat

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I. INTRODUCTION

Tactical missiles for years have utilized solid fueled rockets for their ease of handling, storage, and lighter weight. With new advances in propellants and metallurgy, pressures and temperatures have steadily risen. Although these higher pressures permit the use of a smaller throat, and thus a lighter nozzle, the overall design has risen in either weight or cost or both. This seeming paradox can be explained directly from two factors. First, either state-of-the-art materials with increased strength-to-weight ratios, or heavier supports must be used to compensate for the increased operating pressures. Second, newer, more exotic materials with higher cost must be used to offset the debilitating influence of the higher temperatures.

Designers have explored varying combinations of thrust-time performances, differing grain configurations, and nozzle combinations in an attempt to optimize their particular set of conditions. For many years, boost-sustain motors have been the answer in air-launched tactical missiles. Yet size restrictions, imposed from an aircraft compatibility standpoint, have limited the diameter of the motor casing to approximately ten inches. Thus, geometry plays a significant role in solid rocket design.

Boost motors utilize high pressures, high burn rates, and thus short burn times to accelerate tactical missiles to their

normal operating speeds, and to provide rapid separation from the launch vehicle. This generally has necessitated an internally burning grain and a large nozzle throat area. Sustainer motors, on the other hand, generally use end burning grains, with longer burn times, and pressures ten to twenty times less than their boost counterparts. This has the effect of longer powered flight, at lower accelerations. However, a particular problem occurs when large thrust ratios (five to twenty) are required for the boost-sustain motor. If both modes of operation use the same large boost nozzle, then the sustainer would necessarily operate at very low pressures with often unacceptably low burning rates. Furthermore, to obtain large enough flow rates often requires internally burning grains with their resultant short burn times.

Several possible alternatives are available to the solid fueled rocket motor designer. First, the burning rate of the sustainer motor can be increased. In principle, this could allow the use of an end burning grain with small surface area. In practice, however, high burning rates are difficult to obtain at low pressures. Separate boost and sustain motors could be employed with the booster ejected after burnout. This is often done on ground/ship launched missiles, but this would present difficulties for air launched systems which usually utilize one set of aft mounted fins for trajectory control.

Another alternative is to use a variable area nozzle. Here one nozzle replaces two, but some form of actuation would

be necessary. This, by itself, leads to increased complexity, weight, and expense, not to mention the technical difficulties associated with the high temperatures involved. New technology may permit this concept in the future.

The dual-chamber rocket presents another alternative. In this configuration the sustainer motor incorporates its own optimized nozzle, which allows the use of end burning grains. High pressures are achieved which allow the desired regression rates to be obtained. The sustainer then exhausts into the empty booster cavity, which may either eject its nozzle or retain it.

The dual chamber concept involves some interesting design alternatives. A typical design might incorporate a booster cavity which is nearly fifty sustainer exhaust nozzle diameters in length. From available literature, free jets have been observed to shockdown within eight to ten diameters. As a consequence, the sustainer motor gas mixture would exit into the booster cavity, shockdown, and thus act as a gas generator for the booster nozzle. Hence, thrust could be maintained for longer periods of time, significantly increasing powered range of the solid fueled rocket.

Another alternative for the dual-chamber concept employs the ejection of the boost nozzle. Here the sustainer motor is optimized for atmospheric expansion. Thrust is again provided at pressures commensurate with long burn times. Again, powered range flight is significantly increased.

If the sustainer motor can be made to exhaust through the boost cavity, without shockdown, it may be possible for it to expand perfectly to the boost nozzle exit area. This could increase thrust dramatically over that obtained with shockdown. However, questions need to be answered. Some literature exists for free jet shockdown lengths [Refs. 1, 2, 3], yet little is known about the behavior of confined jets. If the jet reaches the booster cavity walls, severe problems would certainly arise from high heat transfer rates. This would adversely affect thrust performance, with the increased need for insulation and weight. Moreover, if the booster nozzle is ejected, thrust might drop significantly, as a result of the booster cavity being pumped down. Drag along the walls could also affect thrust.

Benham and Wirtz [Ref. 4] from their studies concluded that the supersonic expansion concept did not appear feasible for the tactical dual-chamber concept. Jet core lengths of only nine inches in booster cavities of thirty to forty-five inches of a typical eight-inch diameter tactical missile have been measured. However, these short shockdown distances might still prove beneficial in the Integral-Rocket-Ramjet (IRR), where combustor lengths are shorter and the exhaust jet actually pumps ramjet air.

The purpose of this study was to determine the feasibility and practicality of the dual-chamber concept through a systematic investigation of the pertinent design (nozzle shape and size, booster cavity lengths, etc.) and operational (pressure, etc.) variables.

II. METHOD OF INVESTIGATION

The object of this investigation was to determine the effects of configuration variables on the internal flow field and on the thrust of the dual chamber rocket. To this end, both axisymmetric and 2-D apparatus were designed and constructed for non-reacting flow experiments. The axisymmetric apparatus consisted of a telescoping booster cavity and was used to determine the effects of design variables on obtainable thrust. The 2-D apparatus was designed to provide schlieren observations of the flow field within the booster cavity.

The axisymmetric apparatus incorporated four physical variables which could be changed in a systematic manner. The booster cavity length, l_b, could be varied from nine inches to 0.35 inches. Thrust, pressures, temperatures, and flow rates were measured and recorded as cavity length was varied. Through the slow, steady variation of l_b, the whole spectrum of system conditions could be surveyed in one run. It was for this reason that a telescoping capability for the booster cavity was considered essential. Figures 1 and 2 illustrate the thrust stand and linear bearings utilized to effect this telescoping capability. Figures 2 and 5 show the motor in its full forward position.

Next, two nozzles were designed for the booster cavity to determine the effects of nozzle diameter, d_b, and

booster/sustainer nozzle area ratio. Two sustainer nozzle designs were used to vary diameter, d_s, and area ratios. As a consequence, exhaust pressure to the booster cavity could also be varied. Finally, sustain pressures were varied from 1500 to 300 psia for the conditions noted above.

To summarize, then, four variables were utilized: l_b, d_b, d_s, and P_s. Each was changed and its effects on thrust and booster cavity pressure distribution determined. In a follow-on experiment, a two-dimensional schlieren study will be conducted.

III. DESCRIPTION OF APPARATUS

A. AXISYMMETRIC APPARATUS

The axisymmetric motor was mounted on a thrust stand which utilized linearized bearings to minimize frictional effects (Fig. 1). Figure 3 presents a schematic of the dual chamber apparatus. The high pressure section (Fig. 2) resides within the low pressure section, exiting high pressure air into the lower pressure section, or boost cavity. This closely simulates the solid rocket sustainer motor exhausting into an empty booster cavity. Additionally, the lower pressure section could be translated to alter its length. This can be seen in figures 4, 6, and 7.

To enable the low pressure section to be moved while the motor was operating, a hydraulic pump with a piston attached was utilized (Fig. 8). The piston pushed against the lower portion of the booster cavity, causing it to move towards the sustainer nozzle. However, because of the large moment generated from the pump and booster nozzle acting in opposite directions at high pressures, it was necessary to add stiffeners in the form of two stainless steel bars attached to the sides. Additionally, an I-beam, running the length of the motor directly beneath the point of confrontation, was added to ensure no deflections (Fig. 9).

To ensure that no forces from the high pressure air supply interacted with the thrust developed by the nozzle, two flexible hoses twenty feet in length were utilized (Fig. 9).

The airflow necessary for the experiment was generated by a compressor and stored in 3000 psia tanks. Once into the building, the air flowed through heavy-duty schedule #160 piping, through an air filter, until it reached two Jamesbury ball valves and two Grove pressure regulators (Figs. 10 and 11). The air was routed through an A.S.M.E. flow measuring orifice and then divided into two flexible tubes that connected to the simulated motor.

B. INSTRUMENTATION

Thrust was measured with a strain gage load cell and calibrated using a pulley and weight-table arrangement. Orifice pressure and differential pressure and sustainer cavity pressure transducers were calibrated using a dead-weight tester. Booster cavity length was measured using a linear potentiometer. Pressure distribution within the booster cavity (Fig. 3) was measured using a Statham differential pressure transducer mounted in a 48-channel Scanivalve.

Scanivalve output, orifice temperature, and booster cavity temperature were recorded on strip-chart recorders. All other variables were recorded on an 8-inch Visicorder.

C. TWO-DIMENSIONAL SCHLIEREN APPARATUS

The 2-D schlieren apparatus was designed to provide explanation of the flow phenomena occurring within the booster cavity of the axisymmetric apparatus (Figs. 12, 13). It was designed for ease of removing the glass sides, so that geometry variations could be effected. The apparatus will be mounted on an

existing high pressure air supply pipe with related schlieren apparatus. A transition section had to be designed and fabricated to transition from circular to rectangular cross-sections (Figs. 14 and 15). The 2-D schlieren was designed to allow variation of the same variables as for the axisymmetric motor: l_b, d_b, d_s, and P_s. Moreover, d_b and d_s could easily be changed so that their effect might be explored. Finally, P_s can also be varied from a maximum of 250 to 100 psia. This part of the investigation is to be conducted after the axisymmetric investigation is completed.

IV. EXPERIMENTAL PROCEDURES

A. CALIBRATION

Prior to the first run of the day for experimental data, calibration was performed to ensure the accuracy of the measurements recorded. First, the position of the booster cavity for the axisymmetric motor was checked at full forward and the full aft position, and recorded on the Visicorder. Additionally, the position at eight inches aft was taken to aid in the collection of data at any desired point. The thrust load cell was then calibrated. A pulley and weight system was designed so that thrust levels from zero to 125 lbs. could be simulated. After zero thrust was set on the Visicorder, incremental weights of 25 lbs. were added and the output voltage recorded on the Visicorder.

Scanivalve calibration was performed electronically, inputting the required voltage to the differential pressure transducer and recording its output on the strip chart. This permitted a convenient method for calibrating for pressures from zero to 400 psia.

Finally, the AMTHOR hydraulic calibrations for the pressure transducers were performed. Pressures were normally calibrated for the range from zero to sixteen hundred psia. However, if a particular sustain cavity pressure was to be run, then pressures of one hundred psia, both below and above this value, were applied and recorded on the Visicorder.

B. EXPERIMENT

At this point, after all calibrations were completed, data could be taken. The inlet valve to the test bay was opened, the valves and regulators actuated and charged, and the bay vacated. Then the shut-off valve at the pressure tanks was opened, allowing air at 2700 psia to enter the test bay and proceed to the Jamesbury valves. Tests were conducted from within an adjacent control room (Fig. 10). The pressure level for the sustain cavity was set by loading the domes of the Grove regulators with nitrogen from high pressure bottles. Instrumentation was turned on, and Jamesbury valves were actuated. If the booster cavity length was to be varied, then a hydraulic pump was utilized to effect the desired transfer from one point to another.

C. DATA REDUCTION

Data were reduced by hand. When sequential tests had slight variations in sustainer pressures, they were corrected to 1500, 1000, 500, or 300 psia as appropriate. An HP 9830 calculator was employed for plotting of all data.

V. RESULTS AND DISCUSSION

The experimental tests produced interesting and sometimes unforeseen results. Discussion of these results will be divided into two sections: booster nozzle attached and booster nozzle removed.

A. BOOSTER NOZZLE ATTACHED

Numerous tests were conducted to measure thrust as a function of booster cavity length. Total pressure and area ratios were varied as outlined in figure 3 (configurations 1 through 3). Figure 16 illustrates how thrust remained constant (for a given total pressure and a fixed booster/sustainer nozzle area ratio) as booster length varied. Figures 17 and 18 present similar data for different area ratios. At no time during the individual runs did thrust ever increase dramatically. This meant that the sustainer motor exhaust jet never completely attached to the booster nozzle, and thus did not increase the effective exhaust area. This apparently resulted from the incompatibility of the booster nozzle contour with the shock pattern from the sustainer nozzle. In the future, however, it may be possible (with the increased awareness developed from the schlieren data) to more effectively contour the booster nozzle so that this concept might be more fully utilized.

Configuration #1 had a slightly underexpanded, and configuration #2 a significantly overexpanded, sustainer nozzle when complete shockdown occurred. Configuration #3 was originally designed to have ideal expansion at shockdown pressure, but operated in an underexpanded manner because of the low booster cavity pressure.

As cavity length was decreased to less than 20 jet diameters, thrust began gradually to increase (Figs. 16, 17, and 18) and booster cavity pressure began to drop rapidly (Figs. 19, 20, and 21). For very short cavity lengths (< 5) thrust increased more rapidly. This behavior apparently results from interaction of the jet with the booster nozzle. At approximately 20 jet diameters (although greater for large booster/sustainer area ratios (Fig. 21)) the jet begins to penetrate the booster nozzle. At approximately five jet diameters (10 for the larger area ratio) the jet passes directly through the booster nozzle. These changes are more apparent the greater the difference between the booster and sustainer thrusts.

It should be observed that thrust and nozzle static pressure (P9) remained practically constant as booster cavity static pressure decreased significantly. Thus, the sustainer exhaust jet provides an approximately constant total pressure to the booster nozzle for all lengths of practical interest. Configuration #2 shocked down appreciably faster than configuration #1 (99% vice 93%) or configuration #3 (40%). This clearly shows that overexpanded nozzle flows cause shockdown

to occur more rapidly. Figure 17 indicates that constant thrust is achieved early, and that the length of the booster is therefore of little consequence. Thus, for design purposes one can rely on constant thrust, with little consideration given to length. However, rapid shockdown may cause increased heat transfer problems due to earlier jet impingement on the booster wall. This question cannot be answered until the schlieren work is completed, and the percentage of shockdown pressure is correlated to the jet spreading rate.

Larger booster/sustainer area ratios decrease the shockdown pressure and increase the coupling between the nozzles (Fig. 21). Because of the reduced back pressure, the jet penetrates further into the booster cavity before shockdown occurs. However, even for the 20:1 area ratio, thrust did not vary greatly with booster cavity length (Fig. 18).

In most proposed applications of this concept, the booster cavity length is expected to be greater than 35 sustainer jet diameters. For these lengths the above data indicate that jet shockdown will be essentially complete and that thrust will vary only slightly with length. The shorter cavity lengths may be of practical importance in integral-rocket-ramjet applications. However, in that application air would be pumped through the ramjet inlets by the booster exhaust jet. This would affect the pump-down characteristics, and inlet reverse flow must be considered.

B. BOOSTER NOZZLE REMOVED

In the "nozzle off" condition two cases were investigated. Configuration #1 demonstrated the effects of extreme under-expansion of the sustainer flow. Theoretical thrust was 104 lbf. for complete expansion to 14.7 psia, and 91 lbf. for the sustainer exhaust pressure of 320 psia. In the full forward position (no booster cavity) 81 lbf. was measured (Fig. 22). Thus, 10 lbf. was attributed to drag and friction on the thrust apparatus when the booster cavity was full-forward. As the booster cavity length was increased, thrust dropped slowly until 18 jet diameters, where it decreased rapidly with length to a minimum of 29 lbf. (32% of the original value). This drop in thrust was directly attributable to less than atmospheric pressures being developed within the booster cavity for lengths greater than 12 jet diameters (Fig. 23). At the full aft position pressure within the booster was approximately 10 psia. This resulted in a negative thrust force of 61 lbf. acting on the downstream face of the sustainer nozzle. It should be noted that 61 lbf. from the theoretical 91 lbf. yields the measured thrust.

A large thrust variation would occur from sea level to forty-five thousand feet if the aft nozzle were ejected. It could vary from as little as 29 lbf. at sea level to as much as 188 lbf.; a substantial variation. The altitude performance is significantly improved over the "nozzle on" performance, but this wide variation in thrust may not be acceptable for tactical missiles. It is well known in air combat that

most engagements take place below twenty thousand feet. Most pilots would be unwilling to accept such inconsistent performance, especially such poor sea level performance. Additionally, because of extreme underexpansion, the jet spreads to the wall. This could cause high heat transfer rates with increased need for insulation in the booster cavity. It is worth noting that the rapid thrust decay (Fig. 22) began at a length of approximately 18 jet diameters. Large, high frequency oscillations in thrust also occurred for lengths greater than 18 jet diameters. (The top curve in Fig.23 also shows that atmospheric pressure existed in the cavity for shorter lengths). Apparently, the jet expands to the wall at this location. Interestingly, this was approximately the same length at which jet pumping began with the booster nozzle attached.

In configuration #2 (Figs. 24 and 25), a new sustainer jet diameter of 0.465 in. (vice 0.273) was utilized. The jet had increased diameter but lower exhaust pressure and higher exhaust velocity. It attached to the cavity wall at approximately 13 jet diameters (about 20% further downstream than for configuration #1). Decreasing the flow rate (by reducing sustain pressures from 1500 to 300 psia) decreased underexpansion effects and resulted in a more slowly spreading jet (from 13 to 18 jet diameters for expansion to the wall). For an upstream pressure of 300 psia the exhaust pressure was atmospheric.

For the booster cavity in the full-aft position the negative pressure thrust at sea level conditions was 40 lbf. (Fig. 24). Again, there was a 10 lbf. difference between theoretical and measured thrust in the full-forward position. In this configuration the jet expands more slowly and does less pumping down of the booster cavity (Fig. 25). This results in less thrust variation with altitude than for configuration #1. However, the thrust variation is still very large.

For the underexpanded jet the missile must be specifically tasked to operate at high altitudes. Sea level performance is prohibitively low and maximum wall insulation would be required. The sea level thrust penalty decreases as the sustainer nozzle expands more nearly to atmospheric pressure. However, altitude thrust increases are still large. Expanding the nozzle flow more completely also reduces the requirement for booster cavity insulation.

The length of the booster cavity will affect the decision as to whether or not the booster nozzle should be ejected. For long cavities, aft end heat transfer will be high as will thrust variation with altitude.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. BOOSTER NOZZLE ATTACHED

1. Thrust of the sustainer mode of operation does not vary significantly with booster cavity length.

2. Where booster cavity lengths are less than approximately twenty sustainer jet diameters, the sustainer exhaust jet will strongly interact with the booster nozzle. Moreover, booster cavity static pressures decrease rapidly with ever shortening lengths (less than 20 jet diameters), while nozzle total pressure remains essentially constant.

3. The sustainer nozzle gas exhaust never showed any evidence of booster nozzle attachment. At no time did thrust substantially increase as a result of an increase in effective nozzle area ratio.

4. Shockdown depends to a large degree upon sustainer nozzle flow. The extent of expansion determines the behavior of the flow, i.e., whether it will shockdown fast or more slowly. Overexpansion was seen to reduce shockdown distance appreciably. However, it may cause earlier flow impingement on the booster wall.

B. BOOSTER NOZZLE REMOVED

1. Booster nozzle removal led to thrust sensitivity for lengths greater than 20 sustainer nozzle diameters. This was attributed primarily to the reduced pressures on the aft face of the nozzle as the cavity was pumped down.

2. The sustainer flow impinges on the booster wall at approximately 20 jet diameters.

3. Significant promise of thrust augmentation is seen for altitude operations, while unacceptable performance at sea level remains an obstacle.

4. Schlieren studies are required to further comprehend the behavior (shockdown, spreading rate, etc.) of the sustainer jet when it expands into the booster cavity (with and without the booster nozzle).

THRUST STAND

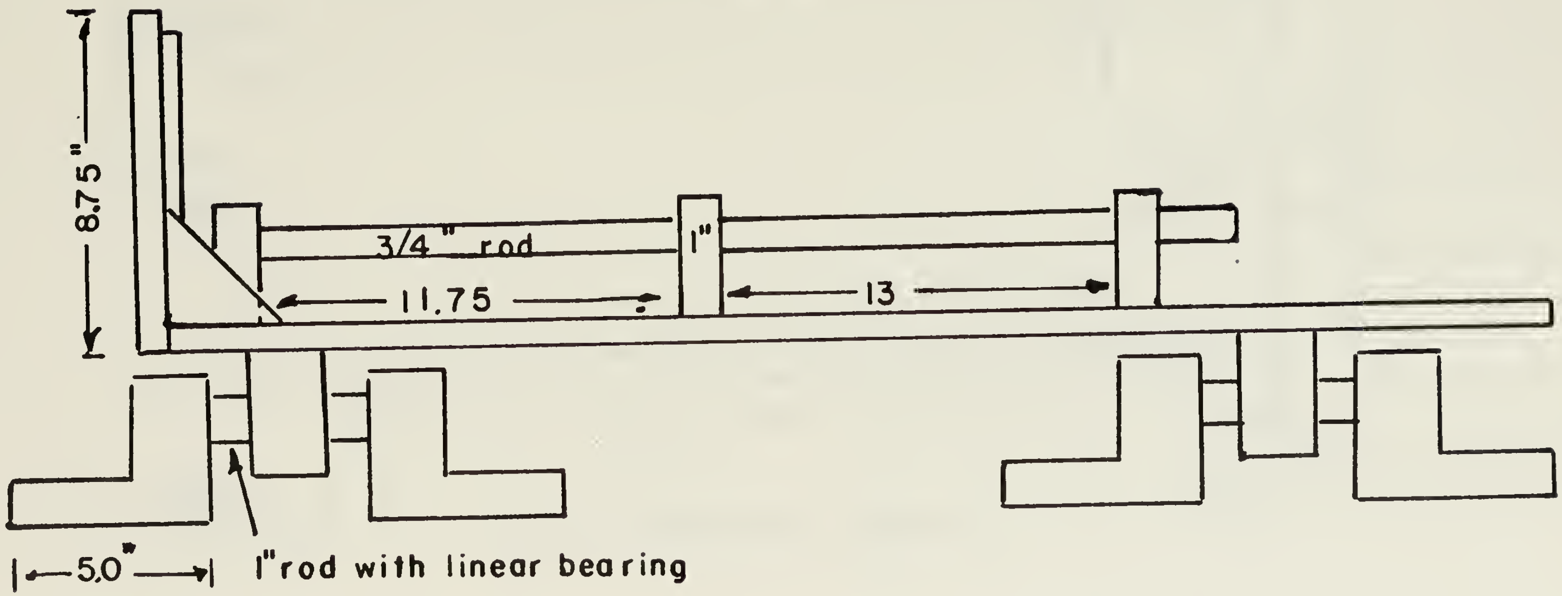


Figure 1. Schematic of Thrust Stand.

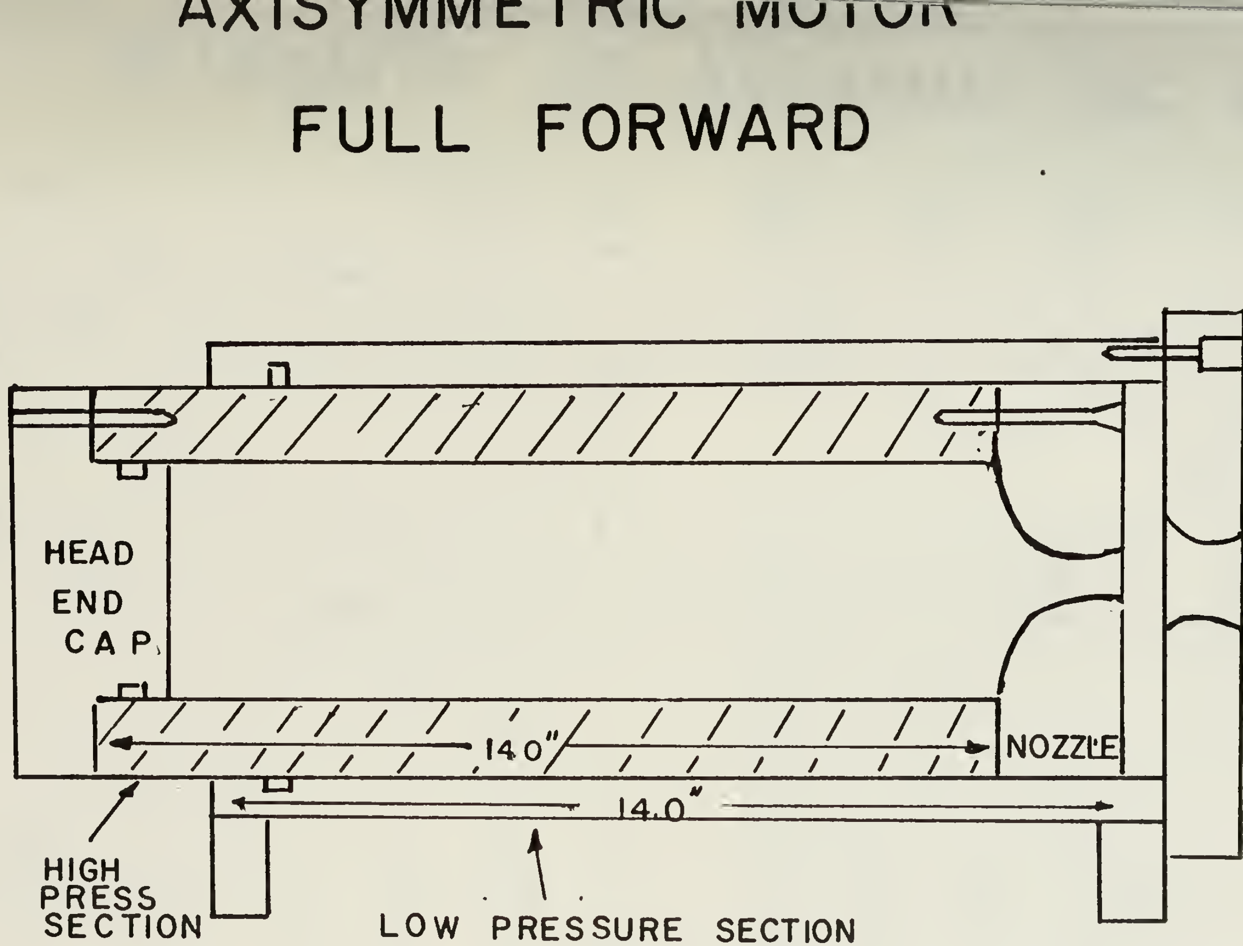
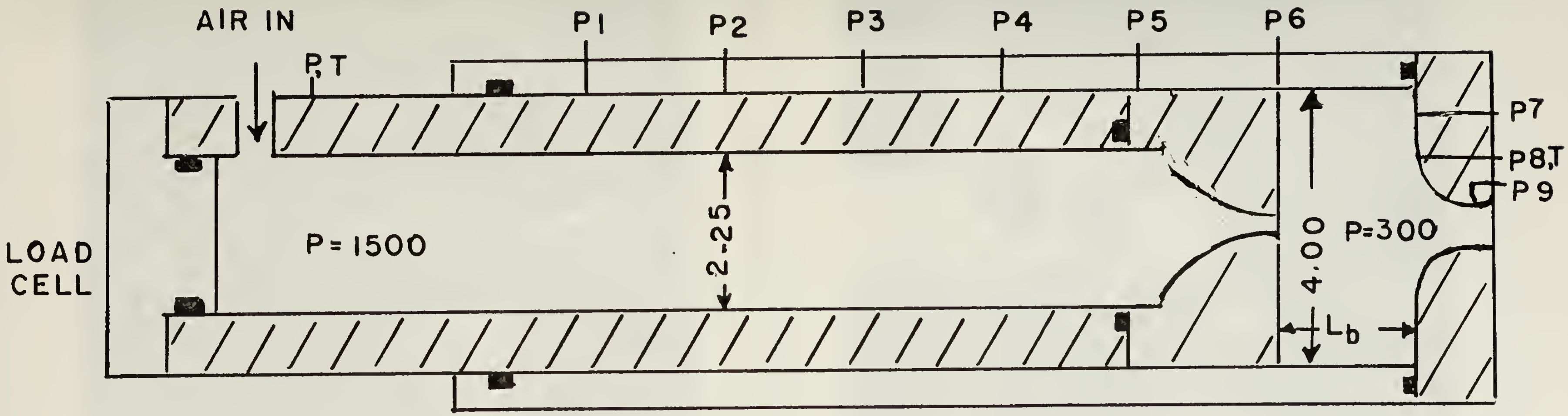


Figure 2. Schematic of Axisymmetric Apparatus.

SCHEMATIC OF AXISYMMETRIC MOTOR



Configuration	d_{t_s}	d_{e_s}	d_{t_b}	d_{e_b}	P_s	P_{sh}	P_{e_s}	P_{e_b}	A_{t_b}/A_{t_s}
(1)	.239	.273	.527	.615	1500	308	320	60	4.86
(2)	.273	.465	.527	.615	1500	402	78	78	3.73
(3)	.273	.465	1.221	1.330	1500	75	78	20	20.0

Figure 3. Schematic of Apparatus and Test Conditions.

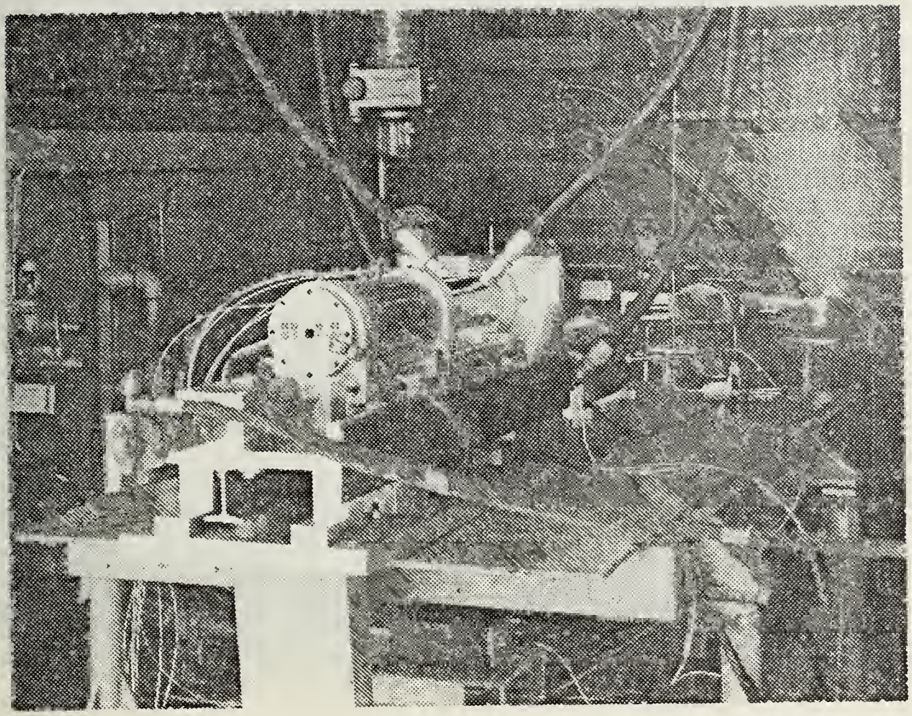


Figure 4. Photograph of Apparatus on Thrust Stand.

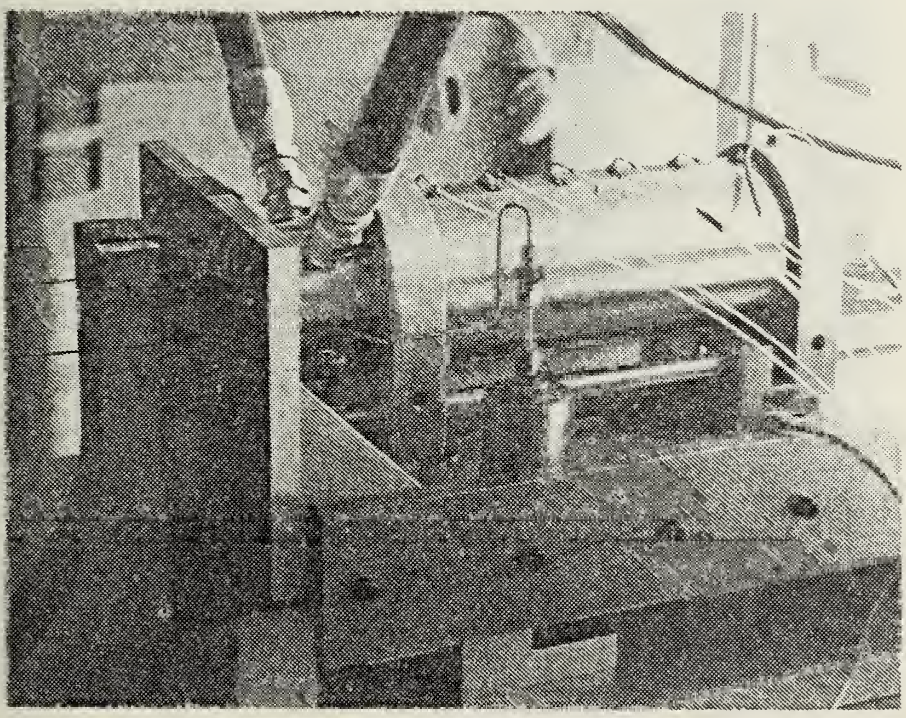


Figure 5. Photograph of Full Forward Position.

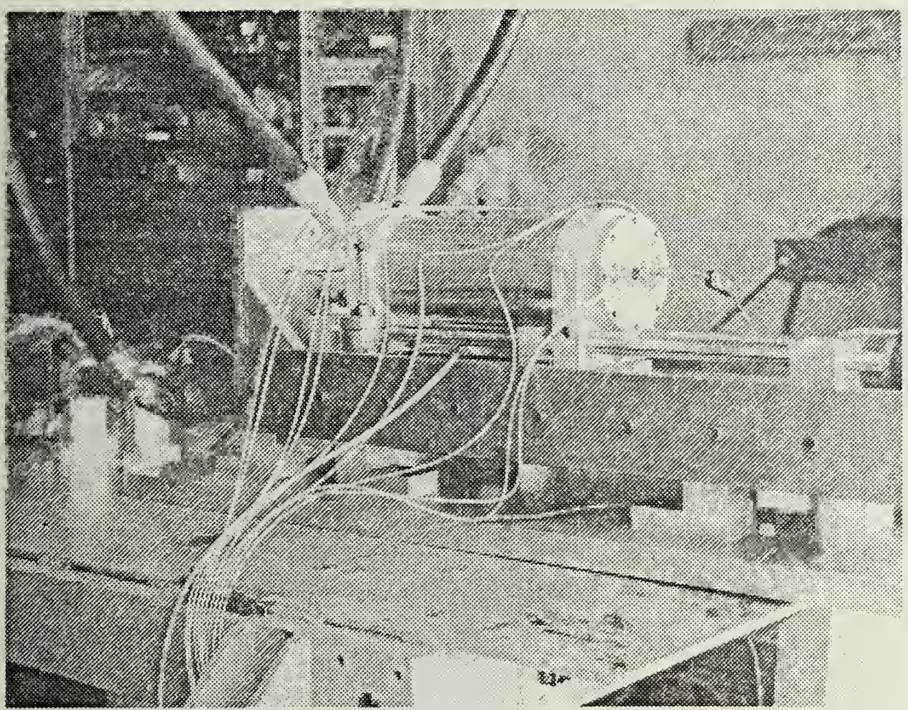


Figure 6. Photograph of Full Forward Position with Instrumentation.

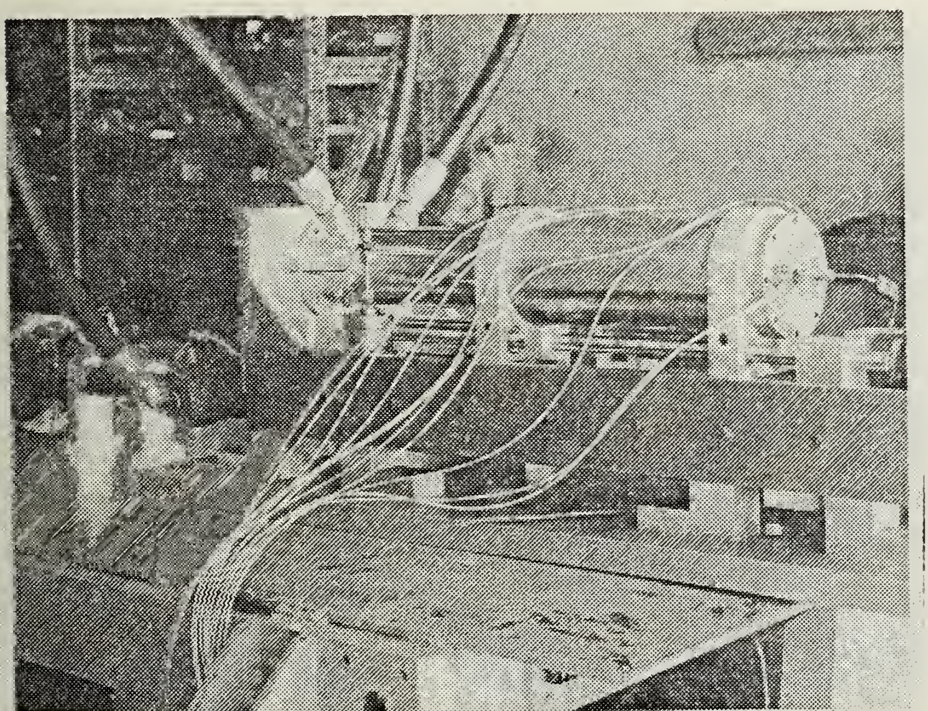


Figure 7. Photograph of Full Aft Position.

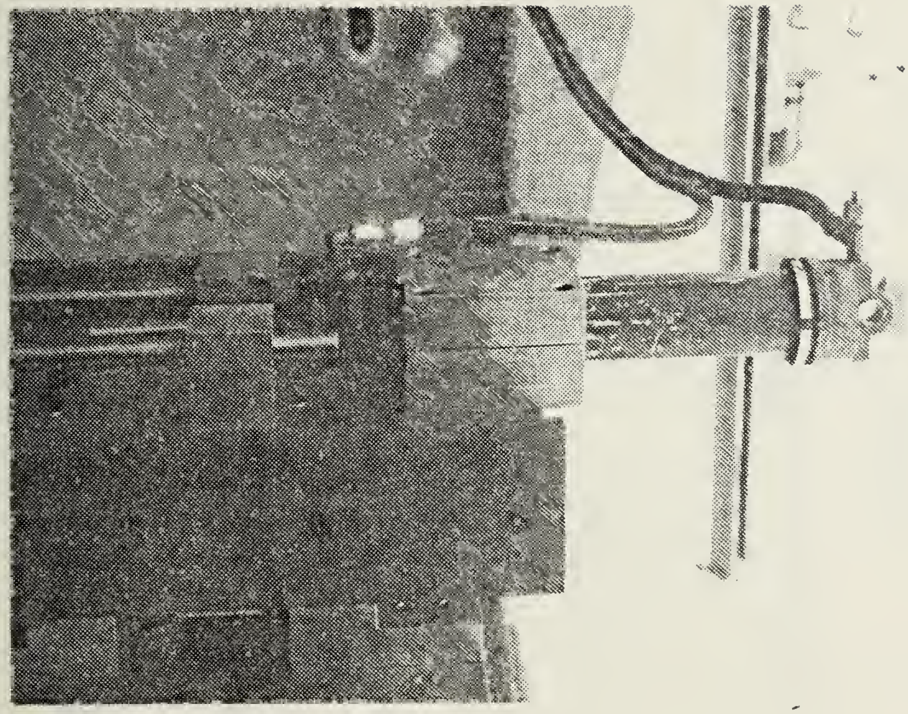


Figure 8. Photograph of Hydraulic Ram.

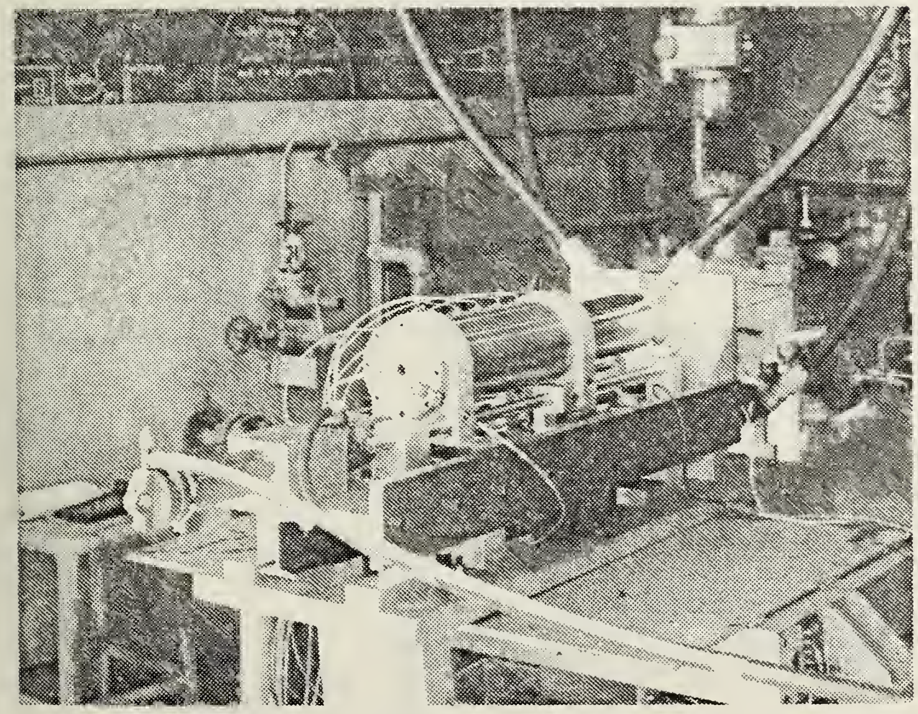


Figure 9. Photograph Showing Thrust Stand Stiffeners.

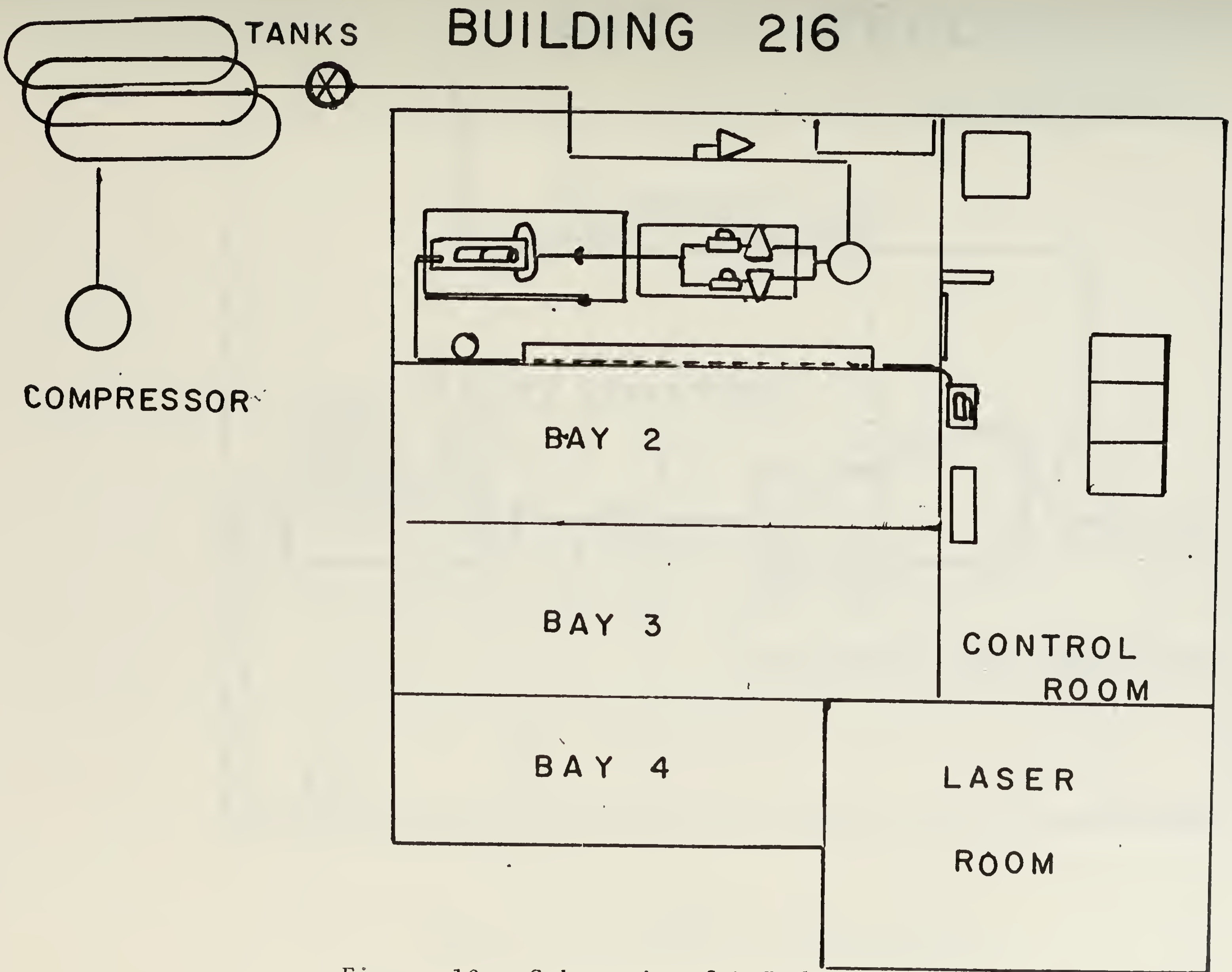


Figure 10. Schematic of Building 216.

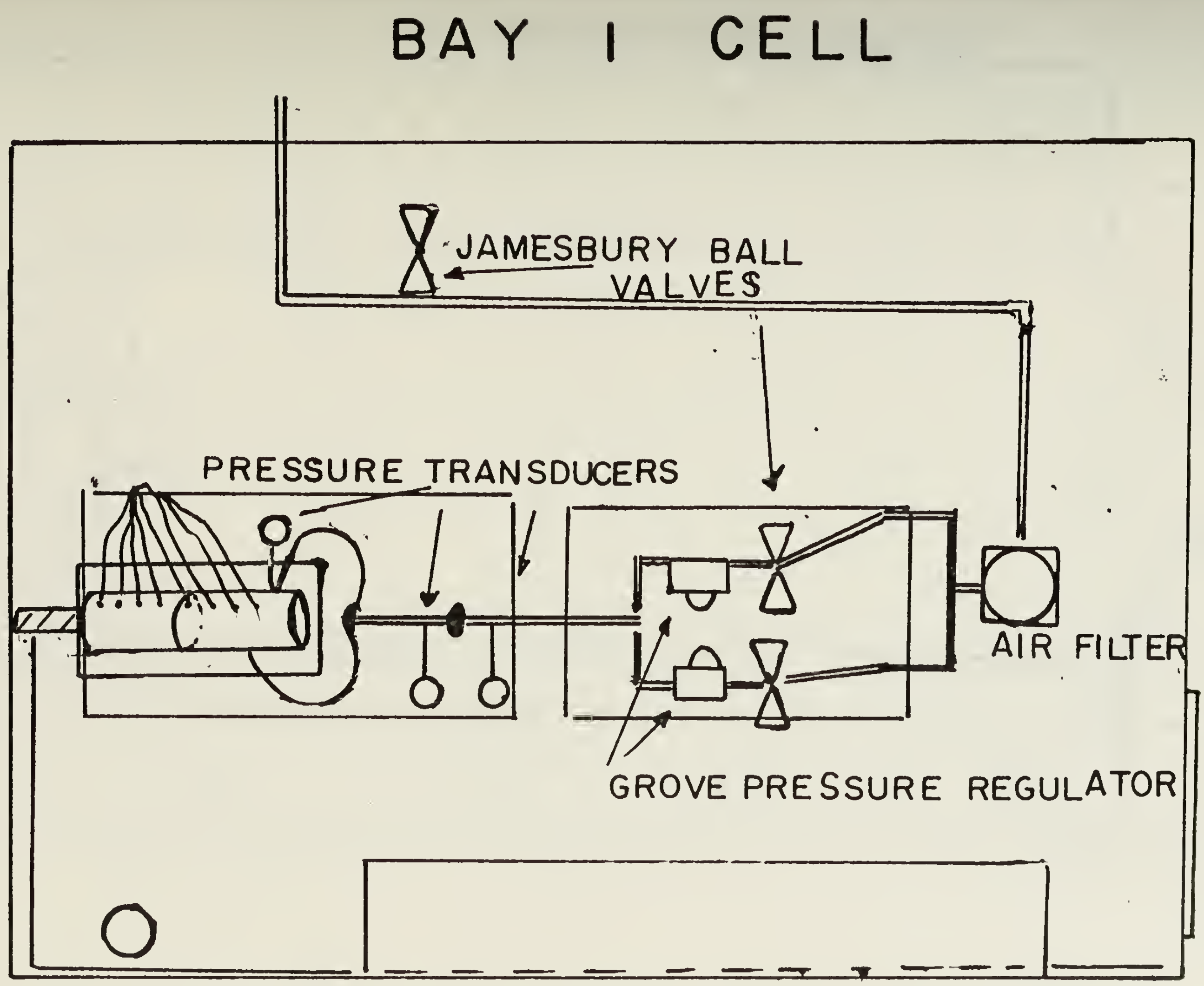


Figure 11. Schematic of Test Cell 1.

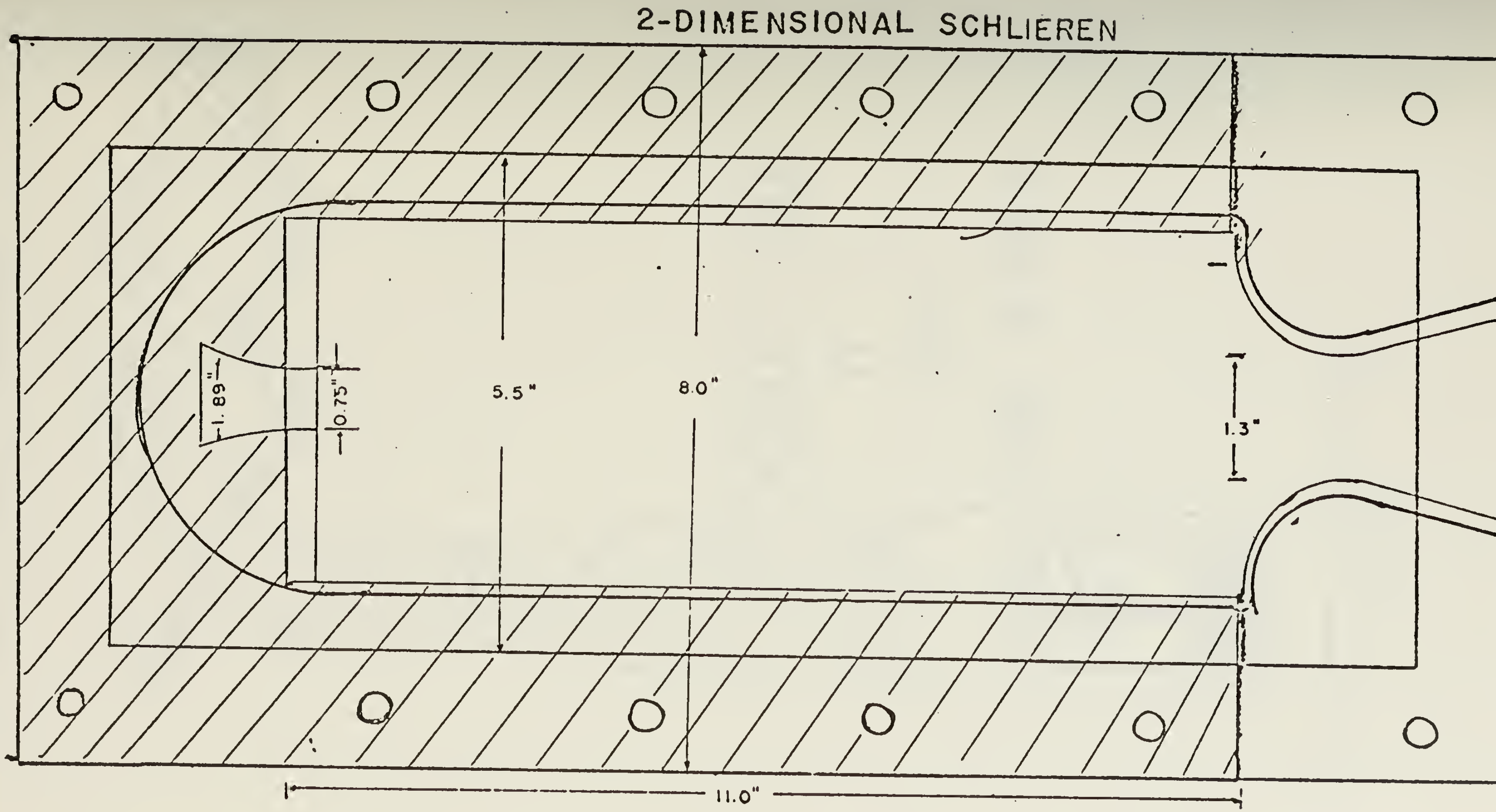


Figure 12. Two-Dimensional Apparatus.

Figure 13. Schematic of Free Jet Equipment.

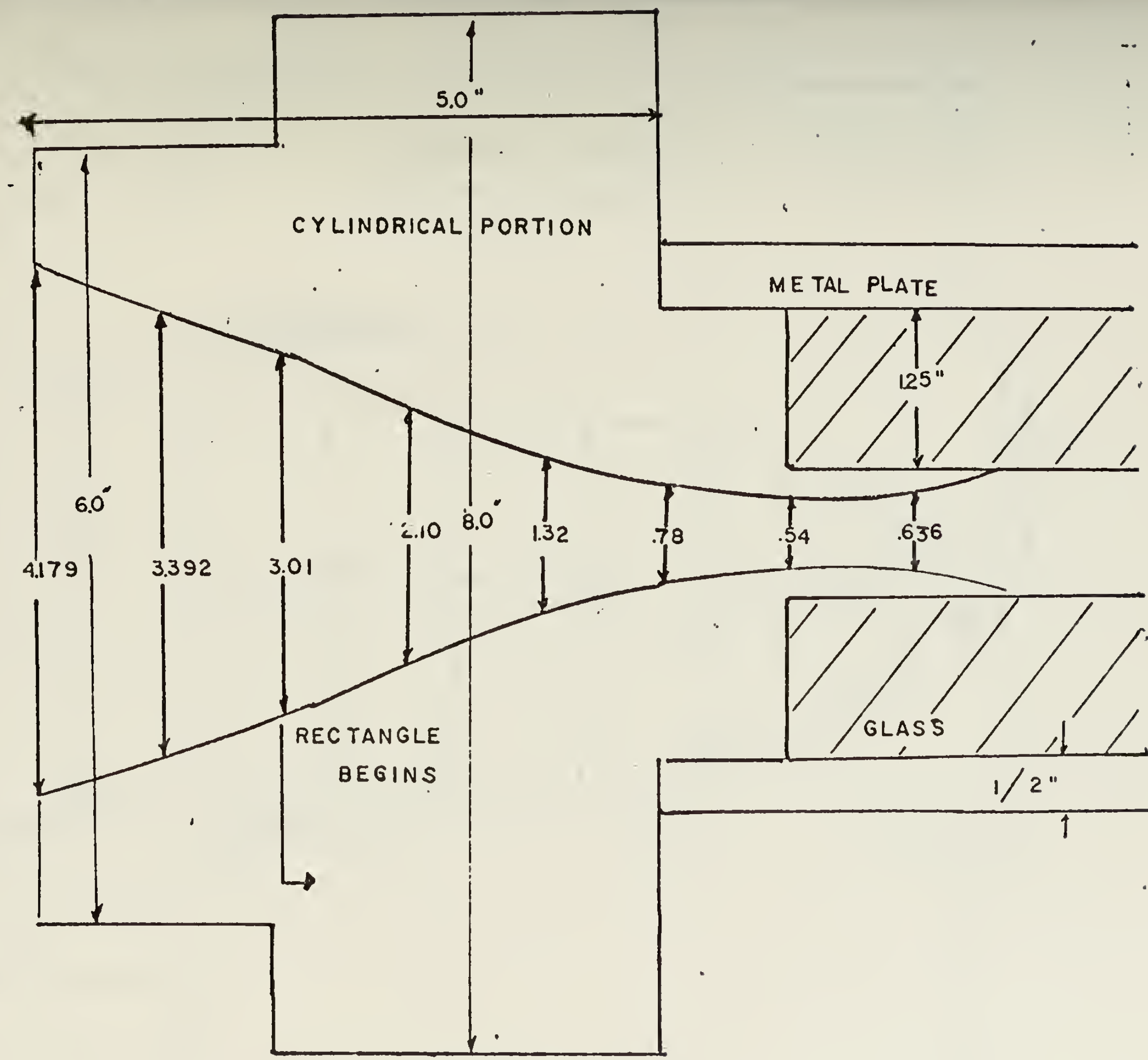


Figure 14. Dimensions of 2-D Nozzle, Y-Direction.

CONTOUR OF SCHLIEREN NOZZLE

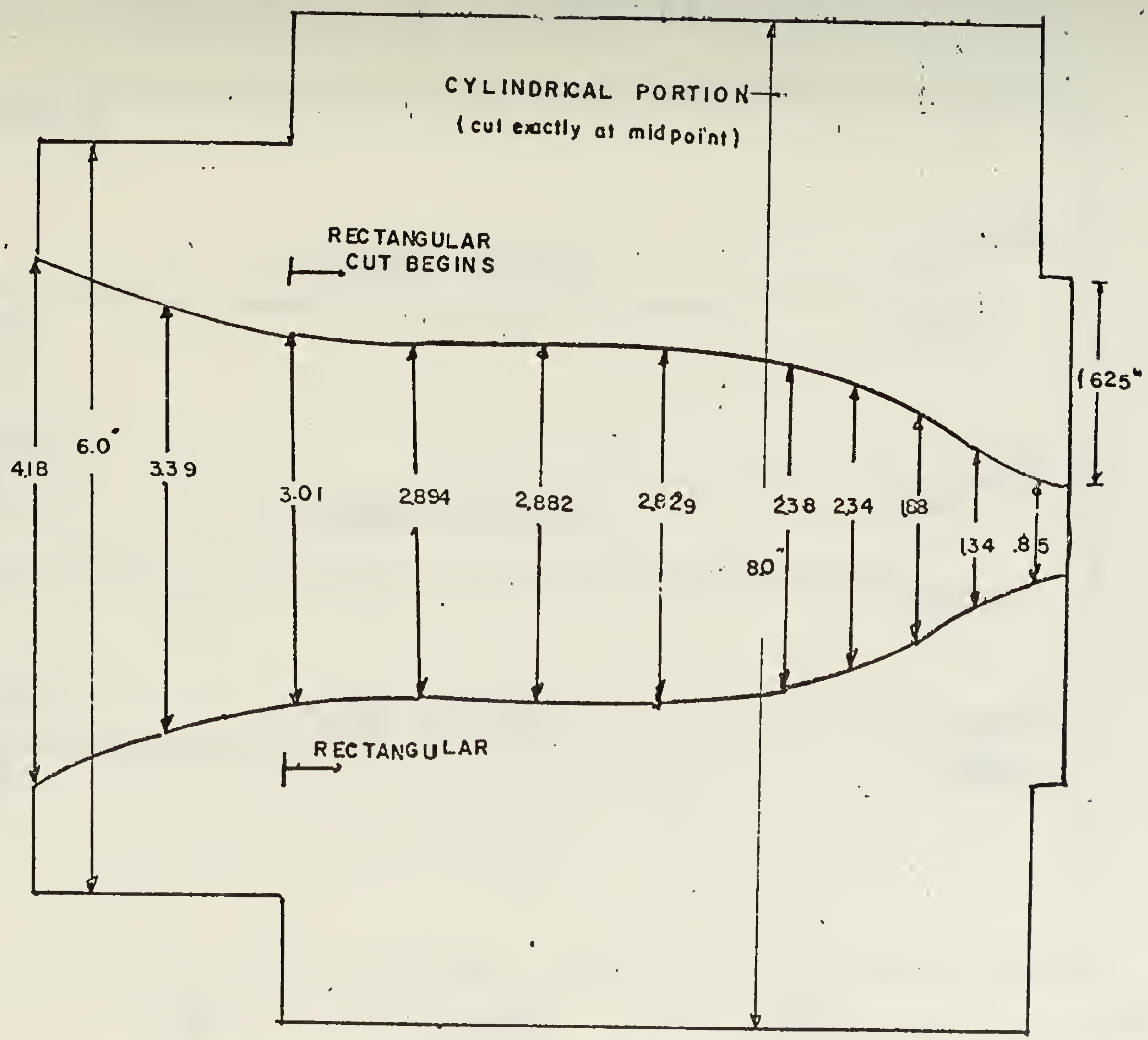


Figure 15. Dimensions of 2-D Nozzle, Z-Direction.

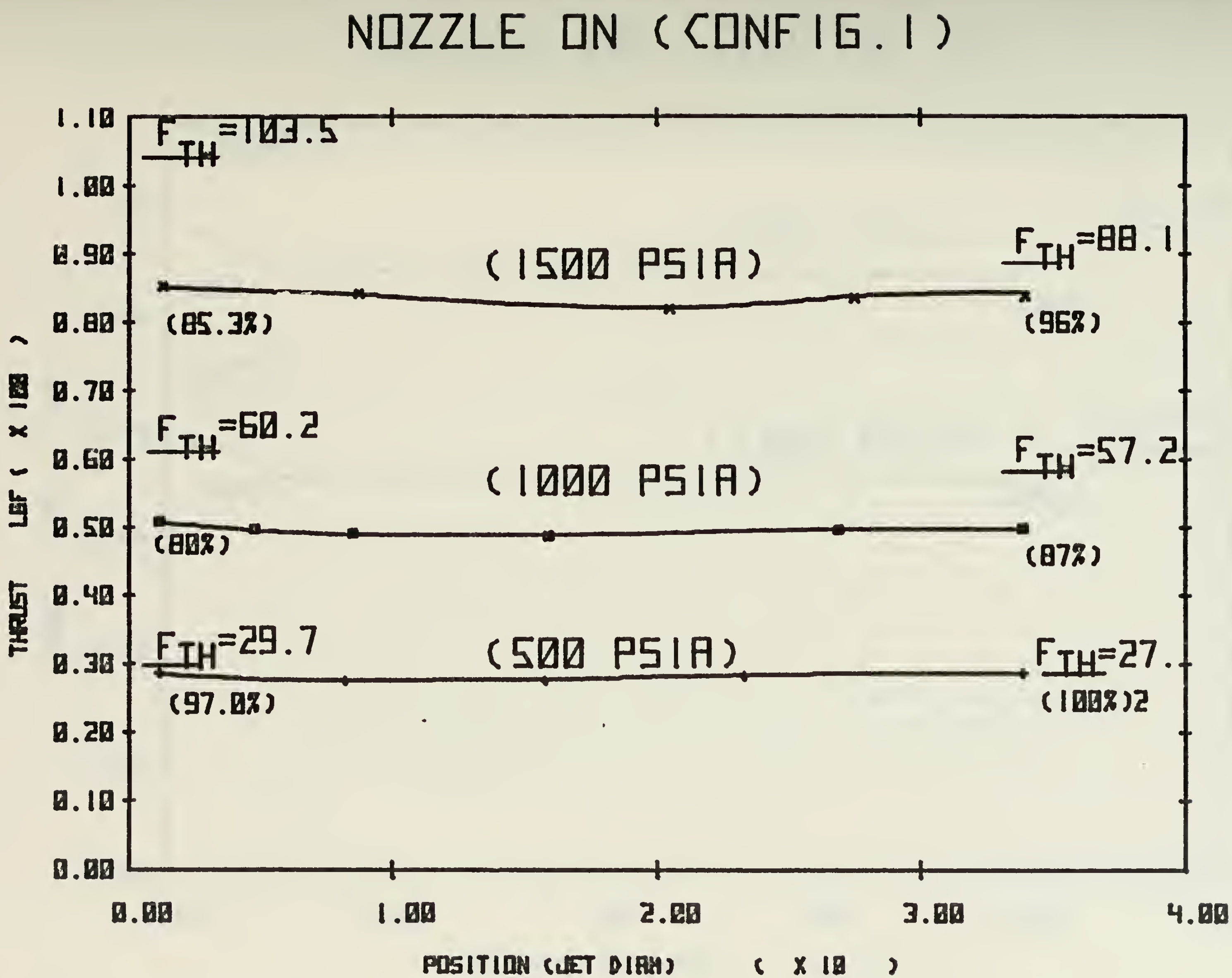


Figure 16. Thrust vs. Booster Cavity Length, Configuration 1, Booster Nozzle on.

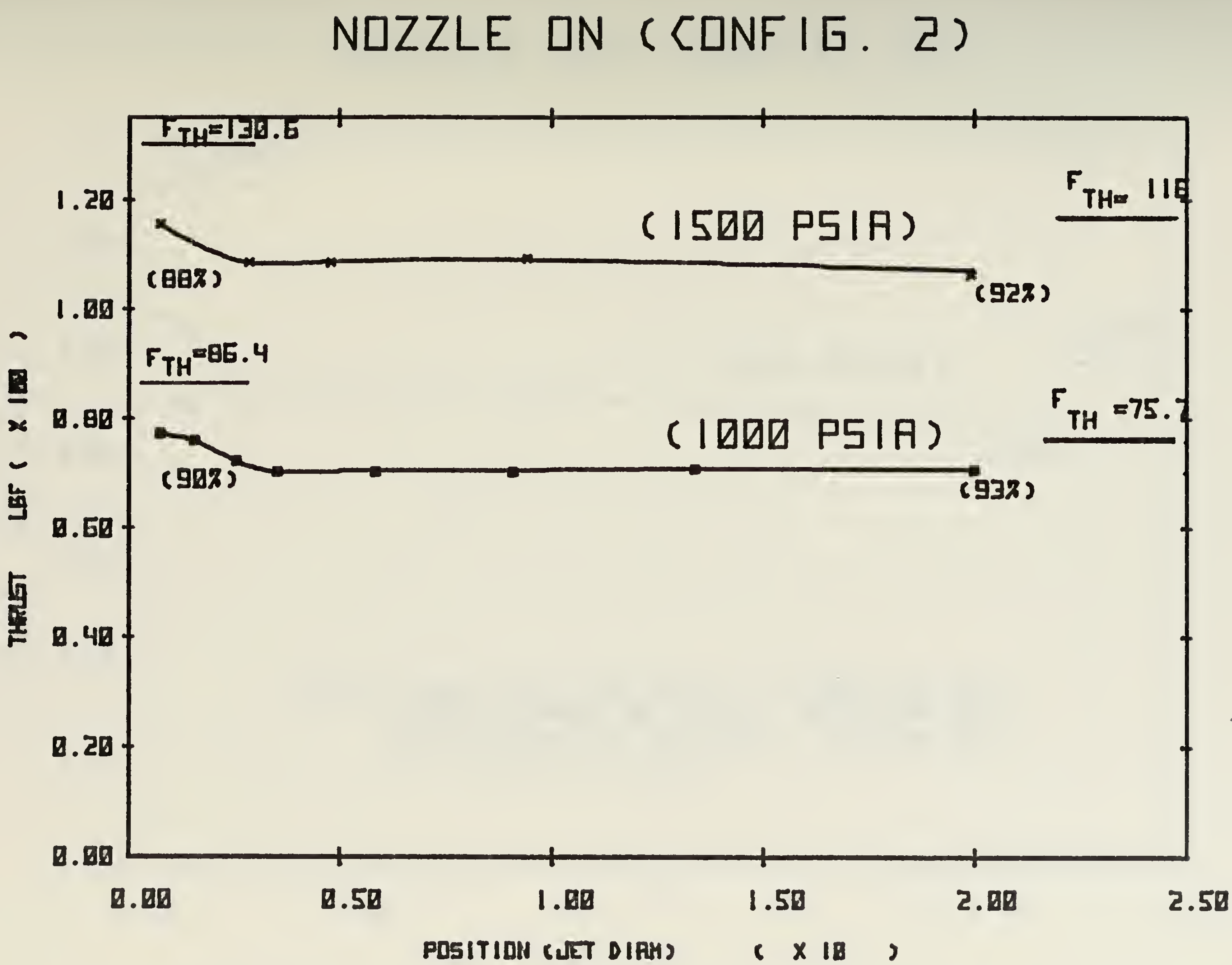


Figure 17. Thrust vs. Booster Cavity Length, Configuration 2, Booster Nozzle on.

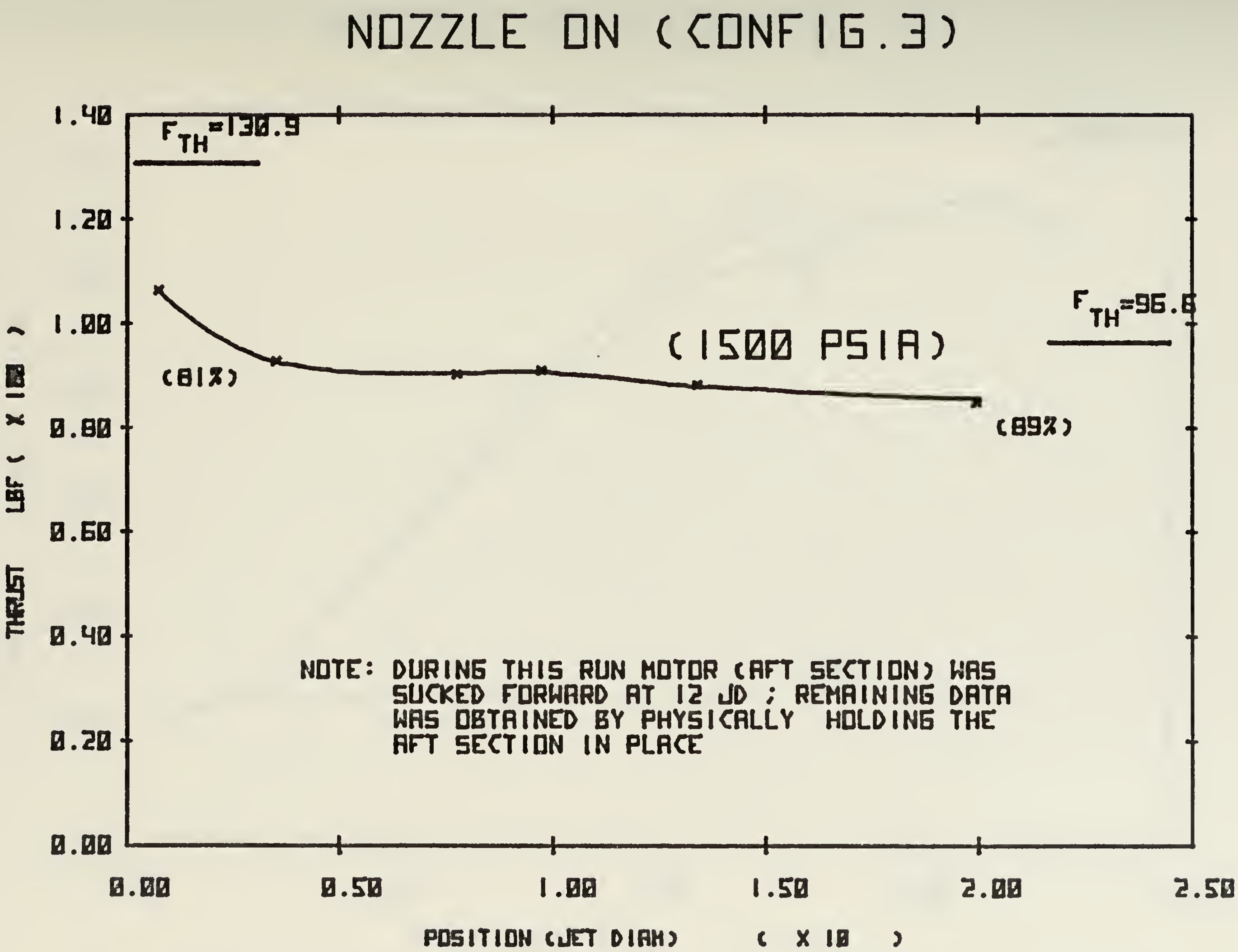


Figure 18. Thrust vs. Booster Cavity Length, Configuration 3, Booster Nozzle on.

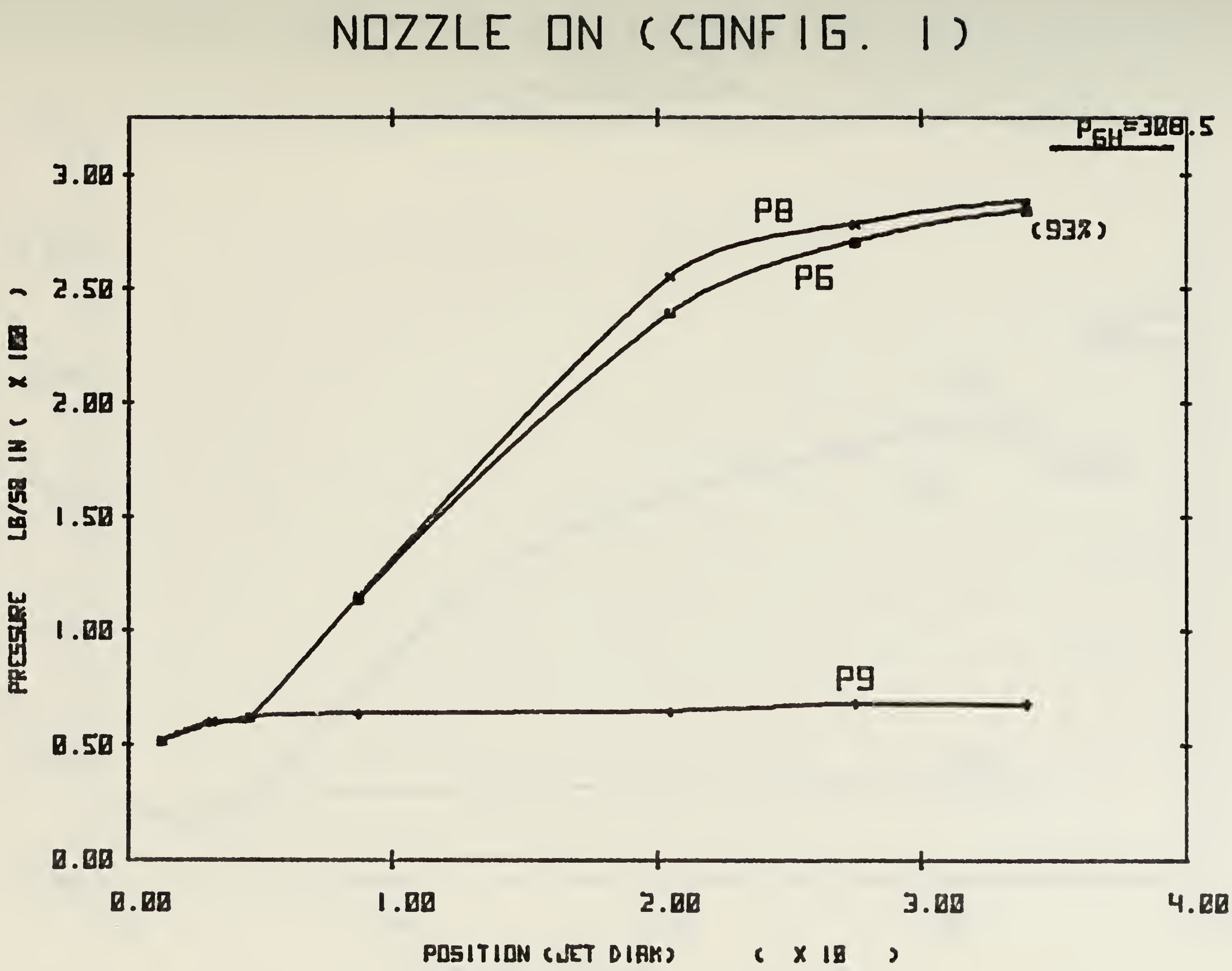


Figure 19a. Static Pressures vs. Booster Cavity Length, Configuration 1, P_s = 1500 psia, Booster Nozzle on.

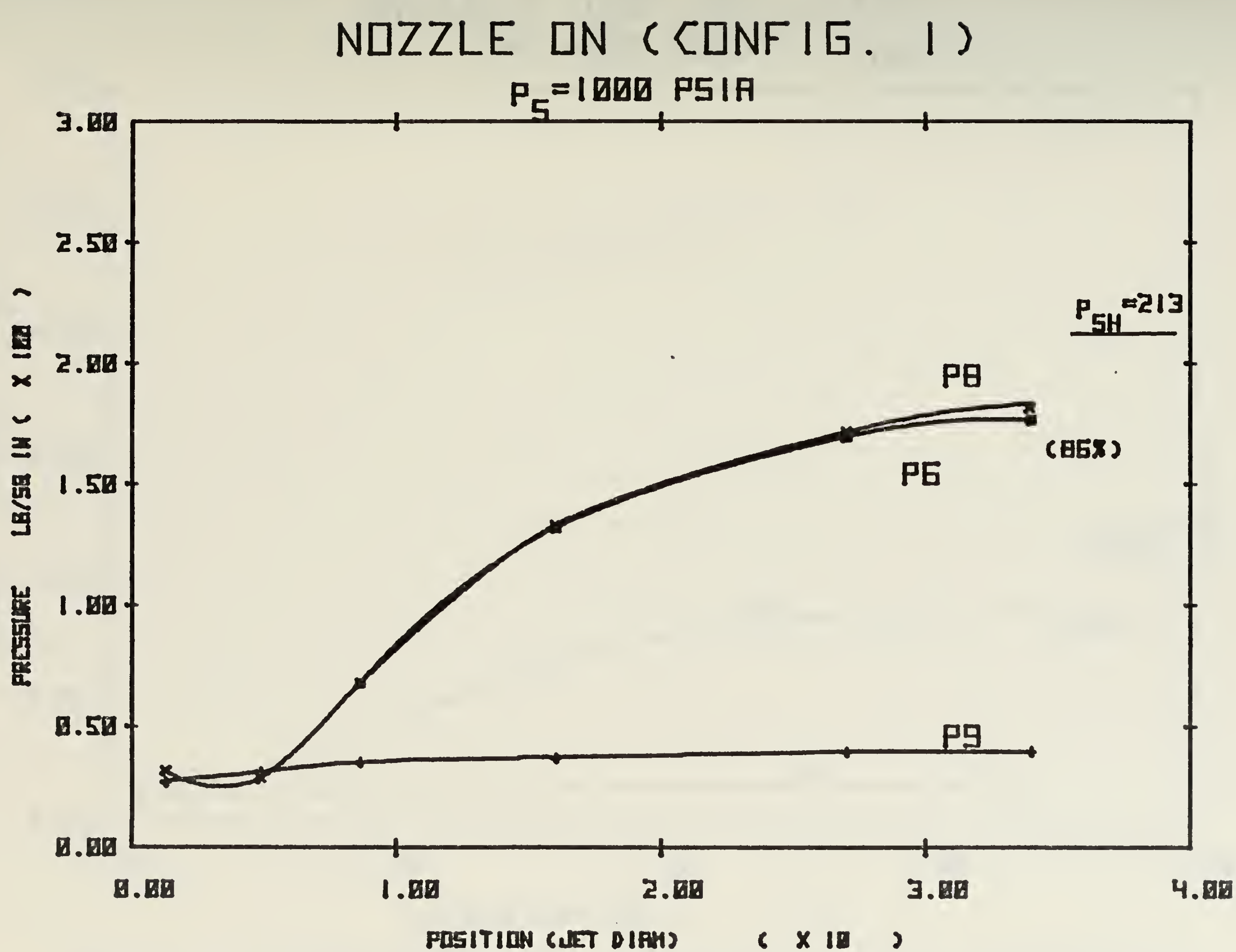


Figure 19b. Static Pressures vs. Booster Cavity Length, Configuration 1, P_s = 1000 psia, Booster Nozzle on.

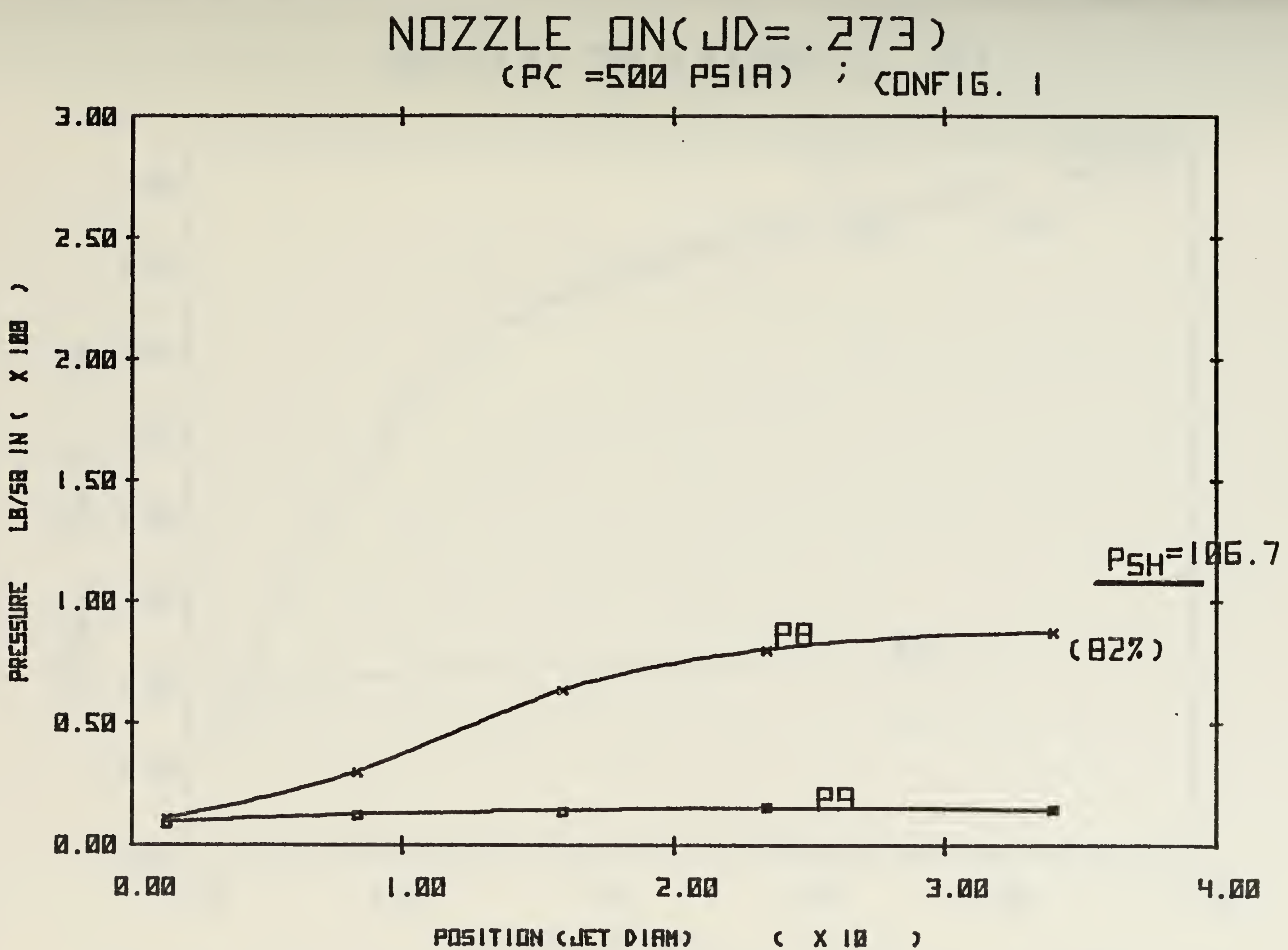


Figure 19c. Static Pressures vs. Booster Cavity Length, Configuration 1, P_S = 500 psia, Booster Nozzle on.

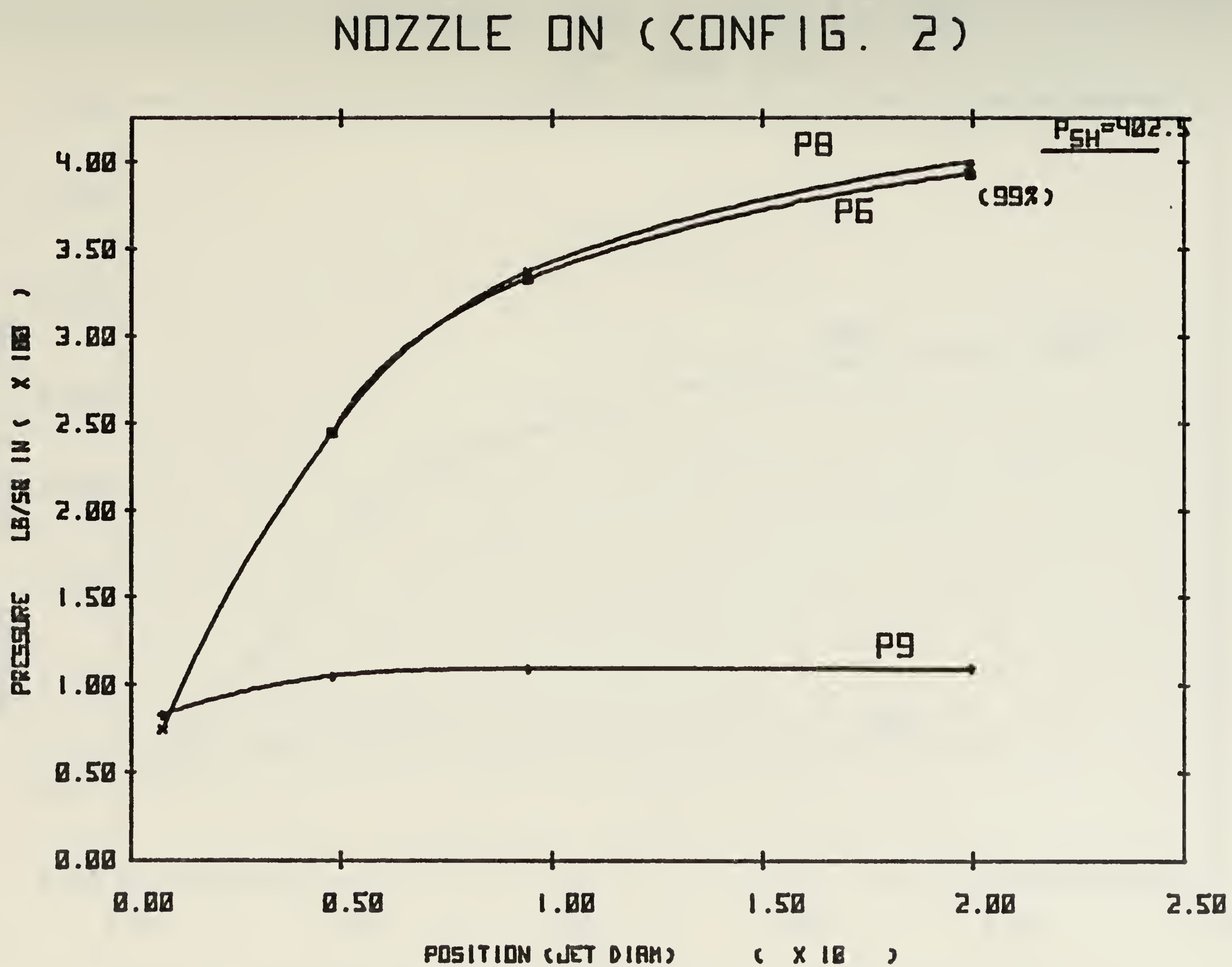


Figure 20a. Static Pressures vs. Booster Cavity Length, Configuration 2, P_s = 1500 psia, Booster Nozzle on.

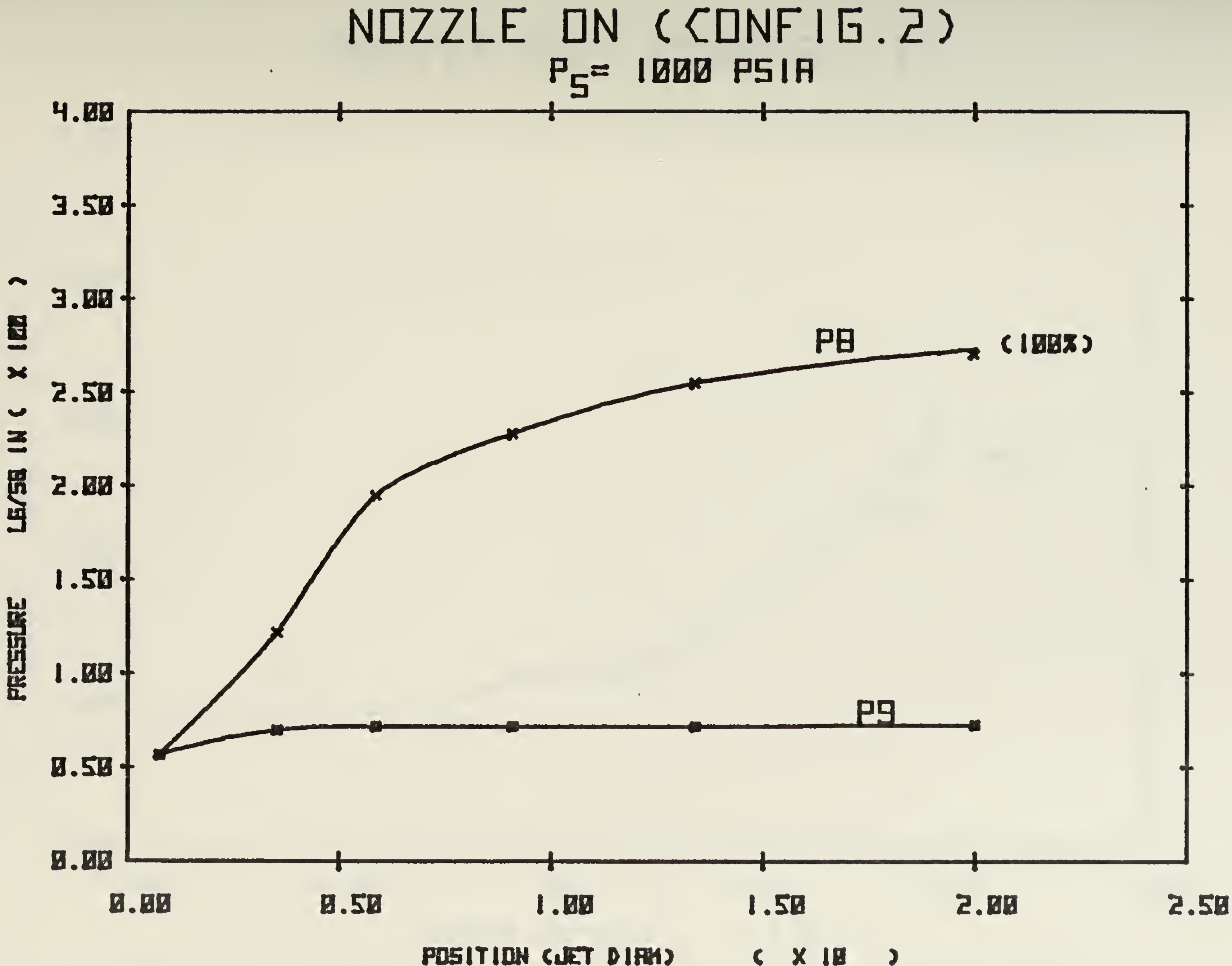


Figure 20b. Static Pressures vs. Booster Cavity Length, Configuration 2, P_s = 1000 psia, Booster Nozzle on.

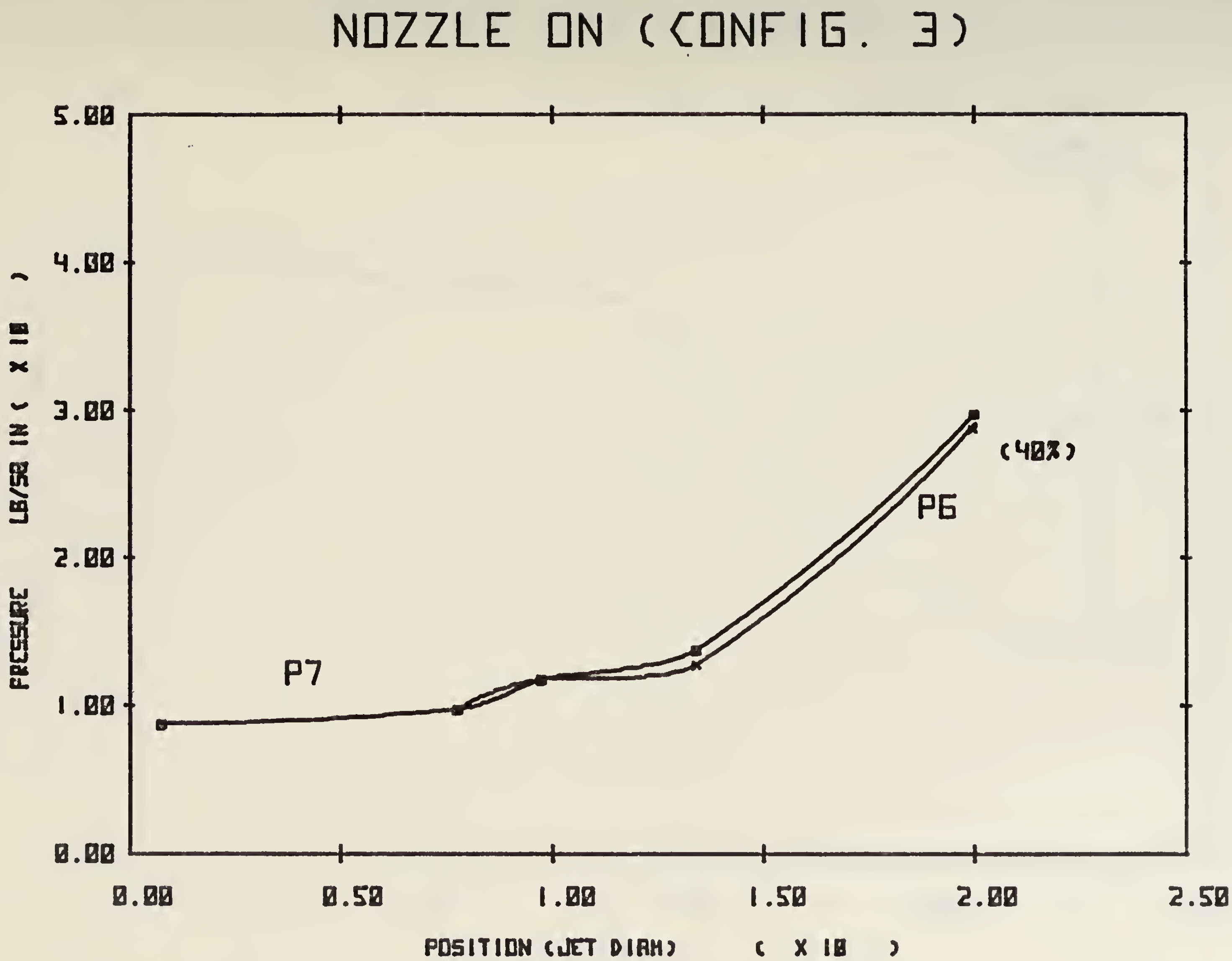


Figure 21. Pressure vs. Booster Cavity Length, Configuration 3, P_s = 1500 psia, Booster Nozzle on.

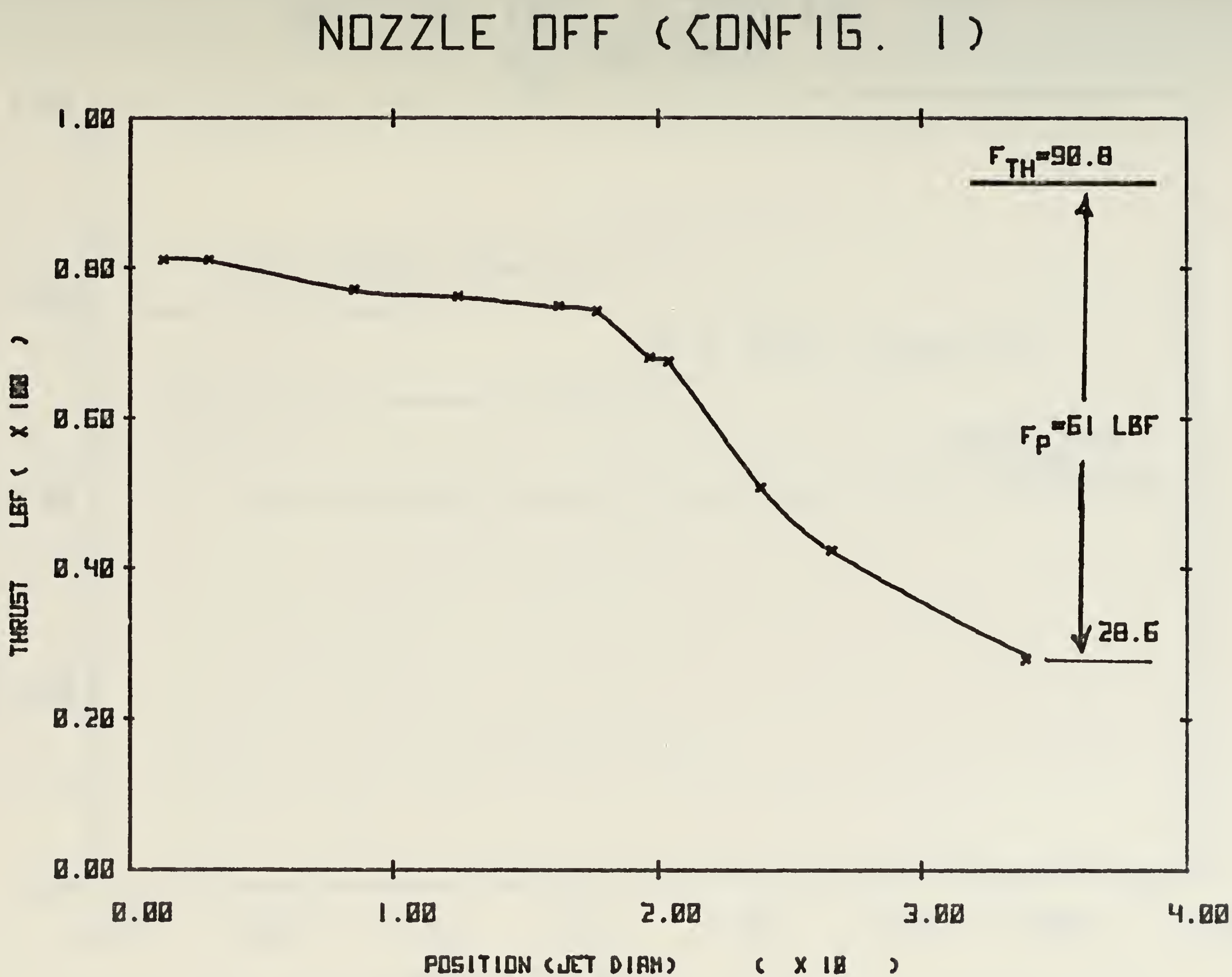


Figure 22. Thrust vs. Booster Cavity Length, Configuration 1, P_s = 1500 psia, Booster Nozzle off.

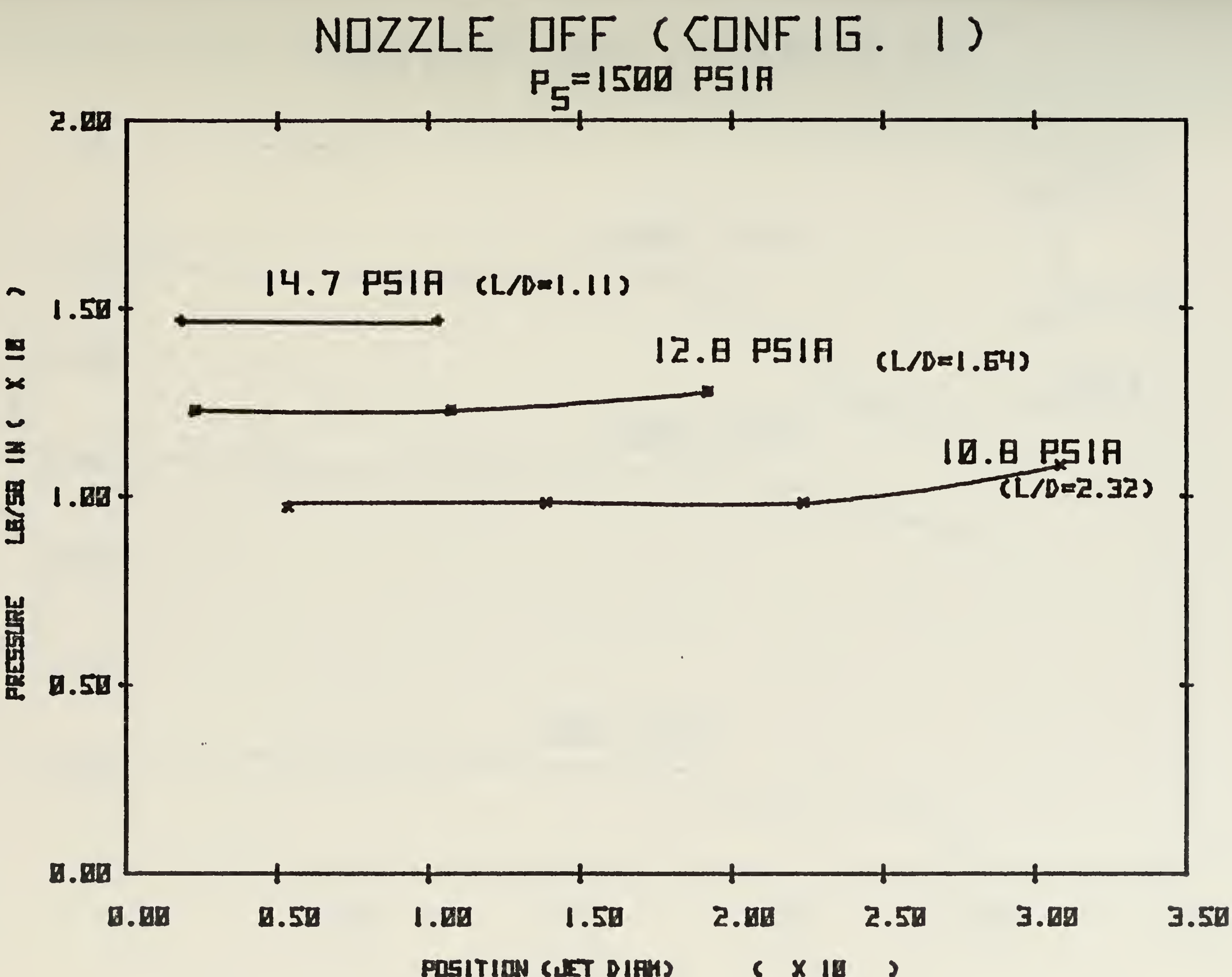


Figure 23. Pressure vs. Booster Cavity Length, Configuration 1, P_s = 1500 psia, Booster Nozzle off.

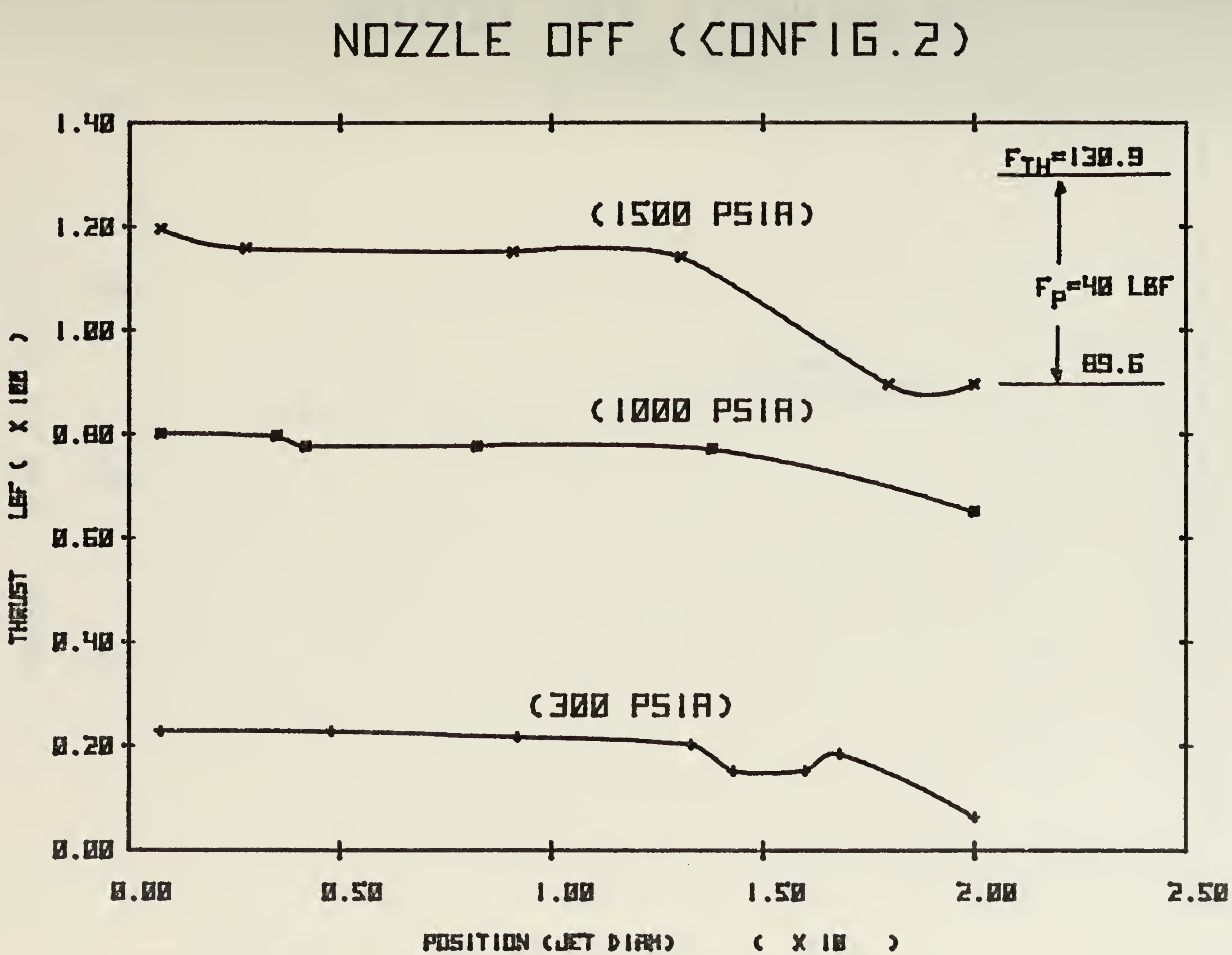


Figure 24. Thrust vs. Booster Cavity Length, Configuration 2, Booster Nozzle off.

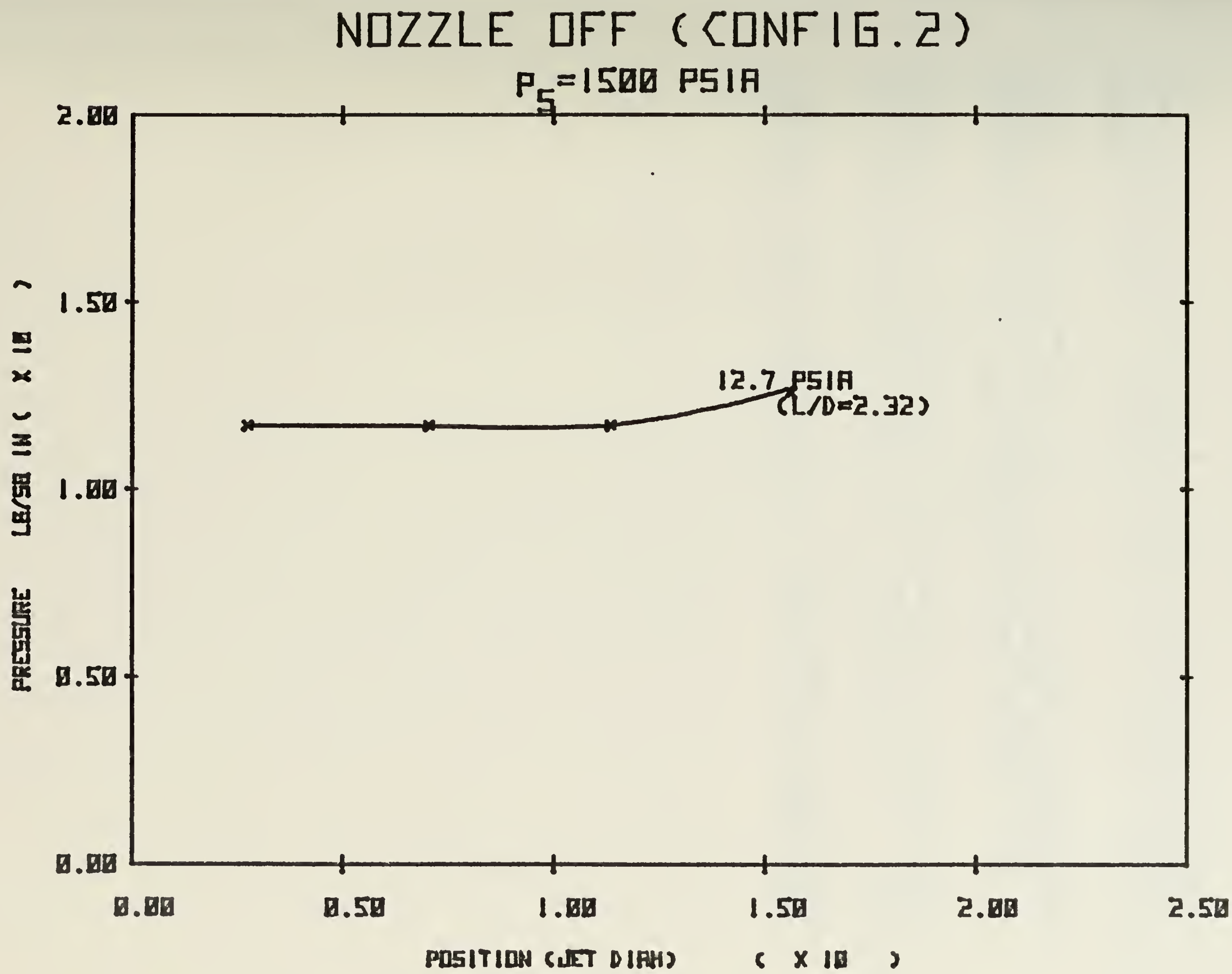


Figure 25. Pressure vs. Booster Cavity Length, Configuration 2, P_s = 1500 psia, Booster Nozzle off.

LIST OF REFERENCES

1. Donaldson, C. and Gray, K., "Theoretical and Experimental Investigation of the Compressible Free Mixing of Two Dissimilar Gases," AIAA J., Vol. 4, No. 11, pp. 2017-2025, November 1966.

2. Tufts, L.W. and Smoot, L.D., "A Turbulent Mixing Coefficient Correlation for Coaxial Jets with and without Secondary Flows," J. of Spacecraft and Rockets, Vol. 8, No. 12, pp. 1183-1190, December 1971.

3. Morris, P.J., "Turbulence Measurements in Subsonic and Supersonic Axisymmetric Jets in Parallel Stream," AIAA J., Vol. 14, No. 10, pp. 1468-1475, October 1976.

4. Benham, C.B. and Wirtz, D.P., "Dual-Chamber Performance Analysis," NWC Memorandum to J. Andrews 3245/CBB: CAS, Reg. 3245-40-77, 5 May 1977.

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